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EXPLORATORY FIRECLIMATE SURVEYS ON PRESCRIBED BURNS

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ABSTRACT

In the summer of 1957, short-term weather surveys were made in four prescribed burn areas in the central Sierra Nevada foothills and in the central Coast Range in California The local fireclimate patterns were studied, a fire-weather forecast was adapted to the burn area for each fire, and attempts were made to note the effects of the fires on the fireclimate patterns. This paper describes the survey techniques used, gives an example of a forecast, and discusses some of the survey results. The latter include an increase in wind speed blowing out of the lee side of the fire, effects of the broadscale weather on the local patterns, down-canyon afternoon winds in east-facing canyons, and temperature observations and topographic effects on the lee side of a ridge.

1. INTRODUCTION

In California more than 100,000 acres of brushland are burned each year under prescribed conditions in order to improve the range land, reduce the fire hazard, or prepare the land for tree planting. The burns offer an excellent opportunity to study the local weather and to note the effects of the fire on it. At the same time fireclimate surveys offer many opportunities for improving the safety and effectiveness of prescribed burns.

A preliminary survey [1] on a prescribed burn on the Lassen National Forest in 1956 convinced us that short-term surveys were feasible in the summertime in the interior of California. Accordingly for the 1957 summer season we selected four prescribed burn areas for study. Two of these were in the western foothills of the central Sierra Nevada and two were in the eastern part of the central Coast Range. In each case an area in rather simple topography was selected.

The objectives of these short-term surveys were threefold:

(1) To determine the local fireclimate patterns and, when possible, note how they are affected by changes in the broadscale weather pattern.

(2) To provide a detailed fire-weather forecast using information obtained on the survey and a general forecast from the fire-weather forecaster.

(3) To note the effects of the fire on the fireclimate pattern.

This paper describes the survey techniques used, gives an example of a forecast, and presents the principal results of each of the four surveys. More detailed information is available in individual reports for each survey [2, 3, 4, 5].

2. SURVEY TECHNIQUES

The survey techniques used were, in general, the same on all four prescribed burns. Equipment was set up and observations started 3 to 8 days before the scheduled date of the burn. Both recording stations and manual instruments were included in the equipment.

Recording stations used Esterline-Angus milliammeter recorders connected to resistance-type wind vanes for wind direction. An auxiliary impulse recording pen was con-

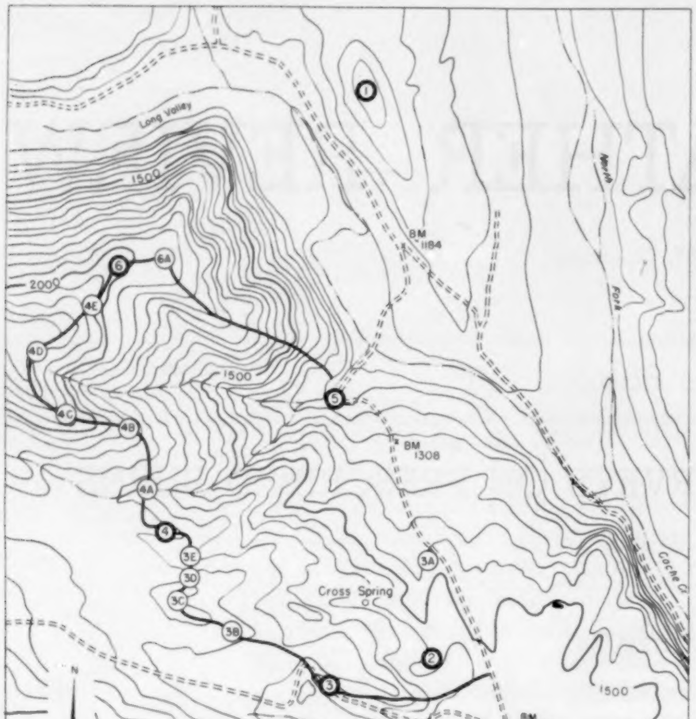

FIGURE 1.—Station locations on Prescribed Burn Survey 3-57, the Ford Ranch in Lake County.

nected to Robinson anemometers for wind speed. Anemometers and wind vanes were placed on tripods and exposed about 10 feet above the ground. Five of these recording units were used on each of the first two surveys and six on the last two. Three 30-hour portable hygrothermographs were used for recording temperature and relative humidity; these were placed in small instrument shelters designed and built for this purpose.

Instruments used for manual observations were Dwyer wind meters and standard wet- and dry-bulb sling psychrometers.

Sites for the recording stations were selected to give the best possible picture of the local weather pattern. Usually some stations were placed on ridges and in saddles on the periphery of the burn area, and others in the bottoms of the main drainage and smaller draws (fig. 1). One well exposed station site was selected far enough from the burn area so that the fire was not expected to influence its readings. This station could then be used for comparison while analyzing the records for fire effects on the local weather pattern. As much as possible, we selected well-exposed sites for the recording stations (fig. 2), but in the bottoms of draws such exposures could not always be obtained.

FIGURE 2.—A typical recording station.

Manual observations were made at a number of selected sites to provide intermittent samples of wind direction and speed, temperature, and relative humidity. By supplementing the recorders, these readings helped round out a picture of the local weather patterns.

All of the recording stations that were considered to be safe from the fire were left in operation on the day of the burn. In addition, we made frequent manual weather observations and took notes and pictures of the fire to document its behavior.

During the course of each survey a preliminary tabulation and an analysis of recorder records and manual observations were made. The purpose was to determine the daily march of temperature and relative humidity, and the patterns of the daytime and nighttime winds, and the times and character of changes. We obtained by telephone from the Fire-Weather Forecast Center descriptions of the general weather patterns. We were then able to associate significant changes in local weather to changes in the synoptic weather patterns.

After the field survey was completed, the data were analyzed in considerable detail. Surface and upper-air weather maps for the period were studied to attempt to explain changes in the local weather observed on the survey. Notes and pictures of the fire were studied with the weather records in a search for effects of fire on the local weather patterns.

3. EXAMPLE OF FORECAST

On the day before the scheduled day of each prescribed burn we telephoned the Weather Bureau Fire-Weather Center for a general forecast for the fire area. Then, using the knowledge of the local weather patterns and their relationship to changes in the synoptic pattern we had obtained from our preliminary analysis of the survey data, we were able to provide a detailed forecast for the burn area. The fire-weather center was contacted again

on the forenoon of the day of the burn to assure that no new conditions would render the forecast obsolete.

The following forecast is the one made for a burn on the Ford Ranch in the central Coast Range and is typical of the forecasts provided:

Fire-Weather Forecast for Prescribed Burn 3–57, August 19, 1957

The weather and wind patterns observed during the past several days will continue today with very little change. The maximum temperatures will be 93–95 and minimum relative humidities 14–16 percent, occurring about 1530 PST. The temperatures will rise rapidly and humidities fall rapidly during the forenoon until around 1000 PST and then change more slowly. The temperatures at 1200 PST will be around 90° and the humidity around 20 percent. Minimum temperatures tomorrow morning 50–65 and maximum humidity 55–65 occurring about 0600 PST. The time of the wind shift from down-canyon to up-canyon tomorrow morning will be around 0600 PST.

Winds during the forenoon will be blowing up the canyon and draws, NE, E, or SE depending upon the orientation, at speeds of 2–4 m.p.h. Between 1000 and 1200 PST the influence of the prevailing W to SW gradient wind will become stronger and result in a shift in the local winds to mostly down-canyon. Directions will vary from SW, WNW—again depending upon the orientation. Winds will become stronger after the shift. Speeds will be 8–14 m.p.h. at higher elevations on the west side of the area with gusts as high as 20 m.p.h. On the east side of ridges and near the top of steep slopes roll eddies will form. Conflicting wind currents along Cache Creek Valley and Long Valley could create erratic wind patterns in the area east of Station 5.

This general wind pattern will continue during the afternoon and even during the evening hours except that at the lower elevations speeds will drop off quickly after sunset. At the higher elevations speeds will remain 6–12 m.p.h. until near midnight and then decrease to 2–4 m.p.h.

Slight cooling aloft, coupled with maximum temperatures in the mid 90's will result in a relatively unstable layer to at least 10,000 feet. Thus a rather tall convective column may be expected.

A map showing the expected wind pattern in the burn area for the scheduled time of the burn was provided along with the written forecast.

Actual weather conditions observed on the day of the burn were very close to predicted values. The up-slope thermal winds continued until about 1000 PST, when the wind shifted to westerly and picked up rapidly in speed to approximately that predicted.

4. SURVEY RESULTS

PRESCRIBED BURN SURVEY 1–57

This burn area was in the lower foothills of the west slope of the Sierra Nevada about 24 miles northeast of Fresno, Calif. Slopes were mostly moderate and the whole burn area had a westerly aspect. Because of limited instrumentation, survey efforts were concentrated on the eastern edge of the area where the hottest fire activity was most likely.

The most important finding in this survey was that of a wind blowing with increased speed out of the leeward side of the fire (fig. 3A). This is contrary to the wind action commonly believed to occur. Previously, most workers thought that indraft into the fire area usually reduces the wind speed and frequently reverses the direction of the prevailing wind on the lee side of the fire. However, before these surveys, little quantitative information was available about wind action as close to the fire as these observations.

The effect is apparent in the record at two Stations, A and B. Perimeter firing first brought fire into the vicinity of Station A about 1148 PST. At this time the wind at Station A was southwest (fig. 4). As the fire built up heat in the heavy fuels in a ravine below Station A, the wind shifted from southwest to west (directly up-canyon and directly from the fire toward Station A) and picked up in speed. Station B, which was not being affected by the fire at this time, showed no such changes. A short time later the fire had again reached another heavy fuel concentration. Again the wind at A shifted to westerly and increased sharply in speed. A similar change in wind direction was noted later at Station B when the fire burned briskly beneath it, but the increase in speed was not evident.

At the time that we wrote our report [2] on this survey we suggested that this wind increase was caused by fire burning in a topographically confined area, so that the heated air created by the fire accentuated the normal up-canyon wind. However, since then another case [6] has come to our attention where a similar wind increase was observed in a less confined area while down-valley drainage winds were occurring (fig. 3B). It was an experiment in which a crib of logs was burned in a large east-west valley. Surface weather observations and double theodolite pibals were taken at several distances east and west of the fire. On the leeward side of the fire a threefold increase in wind speed was measured in the down-canyon direction (out of the fire). This increase was definitely fire-induced since such wind speeds were not measured either on the windward side of the fire or aloft. The explanation given is that the increase was caused by expansion of air resulting from the intense fire. An indraft into the fire on the leeward side was observed only after the down-valley drainage winds decreased and the fire flames subsided.

PRESCRIBED BURN SURVEY 2–57

This burn area also was in the lower Sierra Nevada foothills about 15 miles southwest of Sonora, Calif. Most of the area was on east-facing slopes on the west side of Don Pedro reservoir. The ridge on the western edge of the area was oriented approximately at right angles to the prevailing wind. Where such is the case, experience has shown that erratic fire behavior frequently occurs on the lee side.

During the course of the survey the remnants of a cold front passed through the area and provided an opportunity to see that such a change in the synoptic pattern may affect the local weather. A rather deep layer of marine

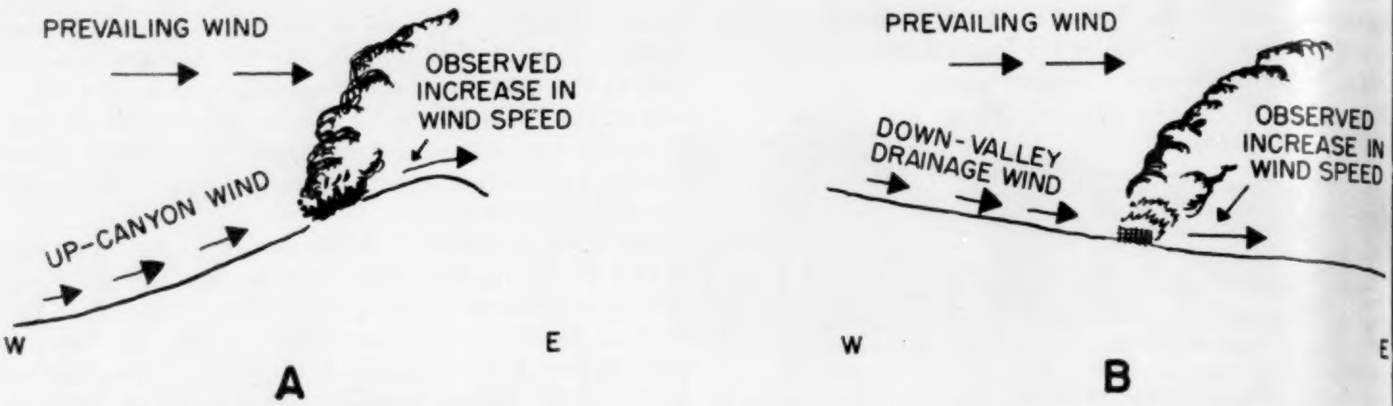

FIGURE 3.—Regions where increased wind speeds were observed (A) on Prescribed Burn 1–57 and (B) on U.S. Army mass fire control test.

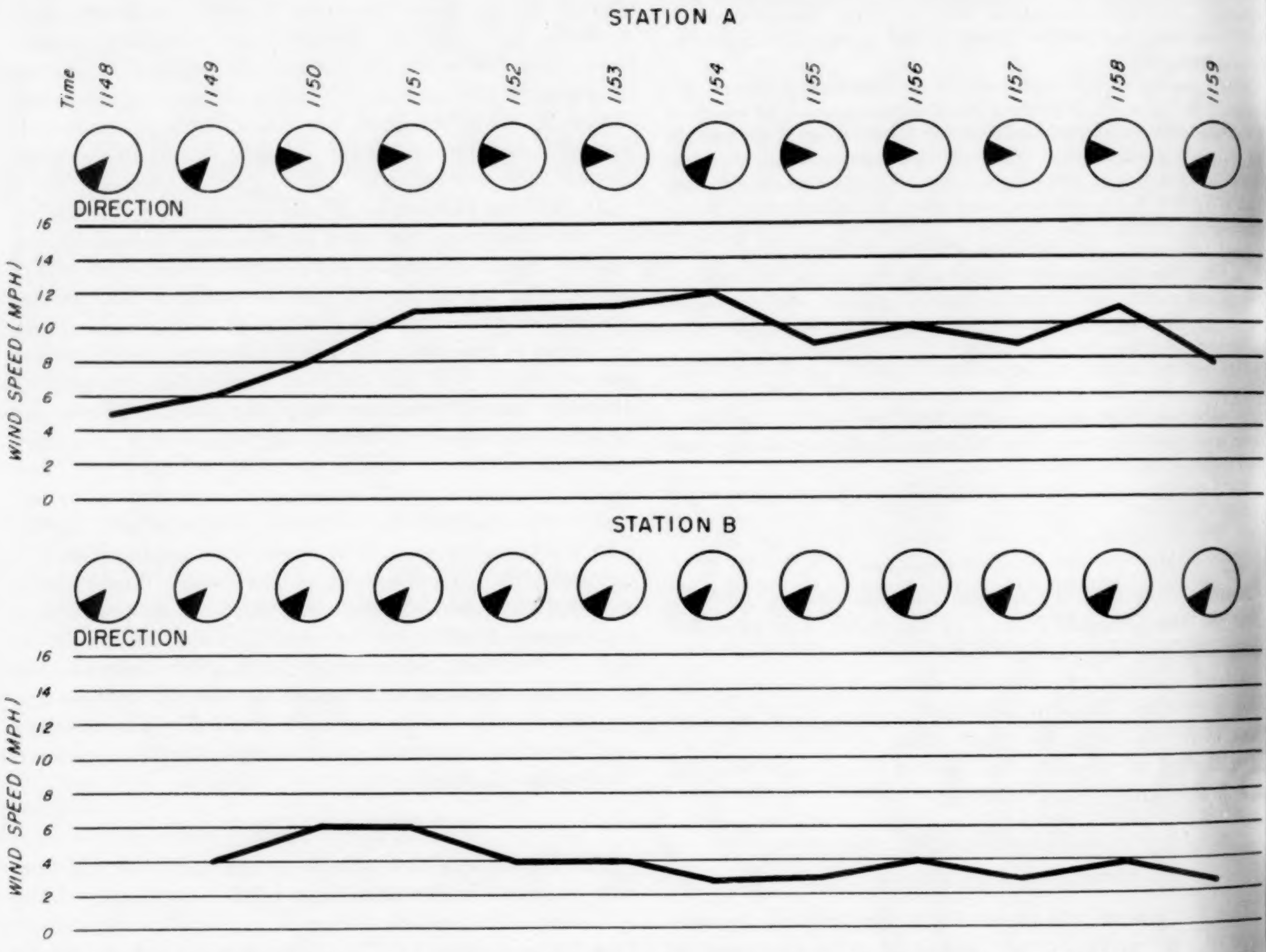

FIGURE 4.—Wind speed and directions at Stations A and B on Prescribed Burn Survey 1–57, 1148 to 1159 PST. North is at the top of the circles.

air moved into the area with the frontal passage, as was evident from the lower temperatures and higher humidities observed at all stations.

The wind patterns were also affected by the synoptic change. Near the top of the ridge the wind direction on most days was southwesterly during the afternoon. On the 2 days when the penetration of marine air was strongest, the wind was westerly throughout the daytime hours. On these 2 days westerly or northwesterly winds were observed in all but the most sheltered areas and the

FIGURE 5.—Prescribed Burn 3–57 at 1134 PST. Note down-slope winds here and in figure 6.

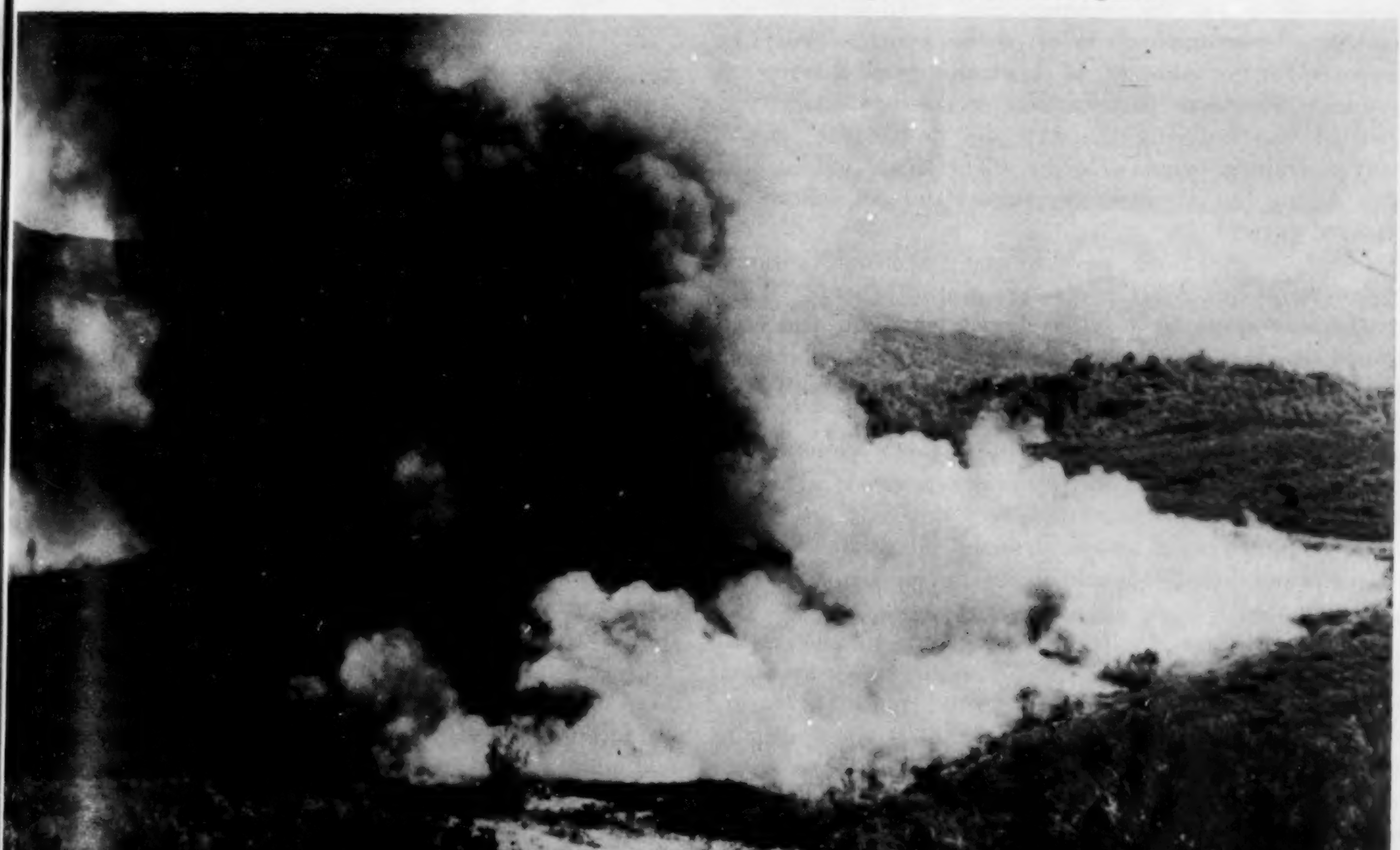

FIGURE 6.—Prescribed Burn 3–57 at 1212 PST.

local thermal wind patterns were obscured. After that the local circulations were again dominant.

Another finding was that in east-facing canyons of the Sierra foothills, the up-canyon thermal wind which sets in early in the forenoon can be replaced during the day by a down-canyon wind. On several days just preceding the burn this change took place about 1000 PST. It was indicated in the forecast for the day of the burn and did occur. These down-canyon afternoon winds were known to occur in various places in the coastal ranges of California but were not known to occur in the Sierra foothills.

A third item worthy of mention is the fact that a firewhirl, which developed in the fire, moved over and upset one of the recording stations. It developed on the lee side of a ridge, an area which is known to be a favored place for firewhirls [7]. In this case the whirl developed in the general area where the survey had shown indications of eddy circulations on previous days.

PRESCRIBED BURN SURVEY 3-57

The third burn area, also with an easterly aspect, was in the Coast Range, in Lake County about 150 miles north of San Francisco and about 60 miles from the Pacific Ocean. The area and station locations are shown in figure 1.

The most important result of this survey was the documentation of the occurrence of down-slope, down-canyon afternoon winds in an area having an easterly aspect. In the absence of a strong general pressure gradient, the classic pattern calls for up-slope, up-canyon thermal winds during the day and down-slope, down-canyon drainage winds at night. The local winds in this area during the course of the survey did not follow the classical pattern.

Shortly after sunrise each morning thermal up-slope, up-canyon winds developed as one would expect. These winds were quite light, averaging 2–4 m.p.h., and continued through most of the forenoon. Then between 1100 and 1200 PST the winds switched rather quickly to a westerly direction and increased in speed. Soon the westerly flow was well established and down-slope, down-canyon winds covered the burn area; speeds of 15–18 m.p.h. frequently occurred in middle and late afternoon. After sundown wind speeds dropped off gradually until more normal down-slope and down-canyon drainage winds predominated.

The down-slope winds are evident from the smoke movement in figures 5 and 6. These pictures were taken looking about south-southwest from the vicinity of station 6 toward stations 3 and 4 (fig. 1). The winds appear to be from about west-southwest. The down-slope winds were of sufficient force to exert almost complete control of the behavior of the fire. Burning embers were carried across Cache Creek. There they produced numerous spot fires, which coalesced into a wide fire front that ran rapidly to the east.

FIGURE 7.—Transect T-1 at northern end of burn, Prescribed Burn Survey 4-57.

PRESCRIBED BURN SURVEY 4-57

The fourth burn area was in the Vaca Mountains in the Coast Range, about 70 miles west of Sacramento, Calif. It was on the west side of a canyon running south-southeastward and extended from the canyon bottom to the ridge top. Of easterly aspect, the area was characterized by several small, well-defined ravines leading into the main canyon (fig. 7). The ravines were separated by spur ridges sloping steeply down from the main ridge.

The most common daytime wind pattern during the survey period was one with a southerly, up-canyon wind in the main canyon, variable winds in the ravines leading into the main canyon and along the upper portion of the slope, and a prevailing southwest or west wind over the ridge tops. Here again down-slope winds were found in the daytime but usually for only short periods of time. This general pattern was not observed on the last two days of the survey when a northerly general wind flow produced northerly winds in the survey area both day and night.

Manual measurements taken along the spur ridge shown in figure 7 revealed interesting wind and temperature patterns. A transect made on the afternoon of September 5, 1957, is shown in figure 8. On the lower two-thirds of the slope the wind direction was generally

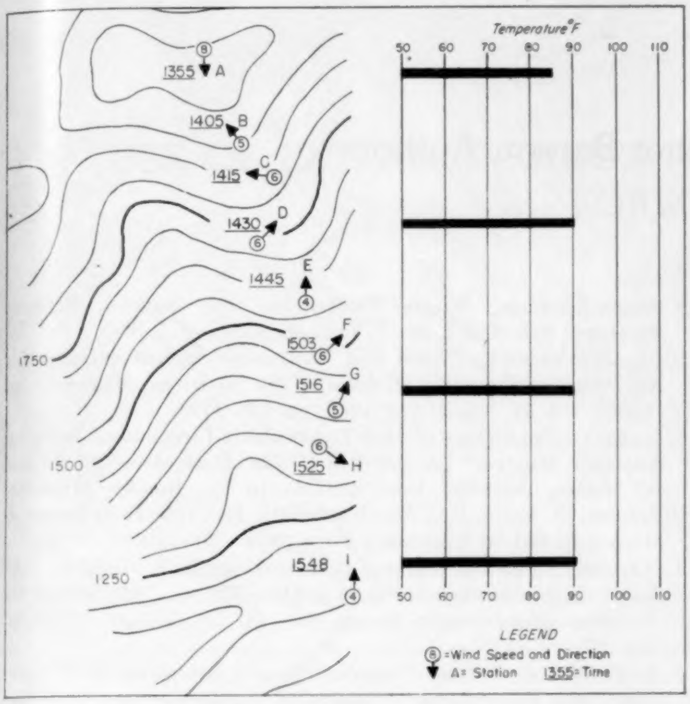

FIGURE 8.—Wind and temperature transect at T–1 (fig.7), September 5, 1957.

up-canyon or quartering up-slope. The prevailing west wind was evident at Station A (the top of the chart is west). The opposing wind directions at Stations A and B were apparent whenever a westerly wind was blowing across the ridge and would indicate the presence of a horizontal or roll eddy along the ridge on the lee side.

The temperature at Station A at the top of the ridge during the warm part of the day was always lower than temperatures taken farther down in the canyon. Other transects where temperatures were taken at all stations revealed the interesting fact that the bulk of this temperature difference occurred in the first 50 to 150 feet down from the ridge top. The readings, of course, were not taken at the same time, but we made a number of such transects at different times during the day and in both directions and all showed similar readings. This strong instability coupled with the mechanically produced roll eddy makes the lee side of a ridge a very critical area—one where erratic fire behavior may be expected.

5. CONCLUSIONS

After these surveys we were satisfied that such short-term operations can be used as an aid in producing detailed fire-weather forecasts for prescribed burns. In addition, they can reveal details of local wind, temperature, and humidity patterns not previously documented, and can point up areas wherein more research effort is needed. As a result of these surveys, we have started a project to study primarily the occurrence of down-canyon afternoon winds in an east-facing canyon in the Coast Range in southern California.

These surveys have also revealed that local wind patterns are extremely complex. They appear to be made up of several circulations of different size scales. First there is the slope wind, and very closely related to it is the circulation in ravines and small side canyons leading into larger canyons or valleys. This circulation can be modified by the circulation in the larger canyon or valley. These circulations in turn may be modified by the larger lowlands-highlands circulation or, if near the coast, by the sea breeze. All of these can be affected in almost any degree by the gradient wind flow and such factors as the character of the topography, the vegetation, and the atmospheric stability. To study these interrelationships we need not only surface weather measurements but also measurements in the vertical, but we do not now have inexpensive ways of obtaining these measurements.

On each of the burns studied so far we determined that the weather pattern was the controlling factor affecting the fire behavior. The actual fire behavior was very close to that indicated by the wind pattern observed. Aside from the very local wind increase on the lee side of the fire in Burn 1–57, there were no other obvious effects of the fires on fireclimate patterns.

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USE OF EXTENDED-RANGE PROGNOSES FOR FIRE-WEATHER FORECASTING

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ABSTRACT

In order to make the regular extended forecasts more directly applicable to fire-weather forecasting problems, the 5-day circulation patterns are studied to determine possible relationships with relative humidity in northwestern Oregon and with thunderstorm occurrences in the northern Rockies. An objective forecast technique is developed for the September afternoon relative humidity in northwestern Oregon. The technique is based on the 5-day mean 700-mb. heights off the coast, the 5-day mean 700-mb. height gradients across the coast, and temperature anomalies for the period from 1949 through 1958. A similar objective forecast technique is developed for July and August thunderstorm occurrences in 10 National Forests in western Montana and northern Idaho. This technique is based on 5-day mean 700-mb. east-west and north-south height gradients and precipitation anomalies over the area for the period from 1954 through 1958.

Contingency tables are prepared and skill scores computed using the developmental observed data and the prognostic data for the same period. The forecasts for the 1959 fire season, which were used operationally, are evaluated.

1. INTRODUCTION

In practice, there has been rather limited application of the U.S. Weather Bureau's extended forecasts to local fire-weather forecasts. The primary prognostic charts are in terms of expected 5-day mean temperature and precipitation anomalies. These are not directly applicable to such weather elements as relative humidity, local winds, and lightning which are of extreme importance in fire control operations.

Probably the principal reason for the failure to apply these forecasts has been the lack of information on the relationships between the prognostic data available to the field forecaster and the weather elements important in fire-weather forecasting. Even to the experienced meteorologist, such relationships are neither simple nor readily obvious. Furthermore, if such relationships exist, they may vary greatly from one area to another due to differences in topography and distances from the various centers of action in the general circulation.

This study was undertaken to examine the feasibility of determining such relations for periods of low relative humidities in northwestern Oregon and for the occurrence of thunderstorms in the northern Rocky Mountain region.

2. RELATIVE HUMIDITY IN NORTHWESTERN OREGON

Periods of low relative humidity in northwestern Oregon during the month of September almost invariably coincide with periods of strong east winds across the Cascades. Extended-period forecasting of this condition is extremely important in the control of fires and slash burning operations during this time of the year.

The data used in this study were for the month of September during the 10 years from 1949 through 1958. The daily 4:00 p.m. relative humidities for three representative stations in northwestern Oregon (Salem, Portland, and Eugene) were averaged over each of the 5 days coinciding with the dates of the extended forecasts. The 4 p.m. time was chosen since this is the time at which most fire-weather data are collected. This time corresponds closely to the time of the lowest humidity, strongest wind, and generally the most critical fire period.

The departure from normal charts very clearly point out significant changes in the mean circulation patterns [1]. The average departures from normal of the pressure-heights at the 700-mb. level that were observed for the period September 19–23, 1957, are shown in figure 1. The average 4:00 p.m. relative humidity over this 5-day period for northwestern Oregon (indicated by star in fig. 1) was 20.3 percent, the lowest of any of the 5-day periods in the 10 years of data. The important feature is the area of intense positive departure from normal in the eastern Gulf of Alaska. In the center of this area, the heights averaged 390 feet above normal. In other words, there was a tendency for an intense ridge to persist over this area during this period. This pattern was

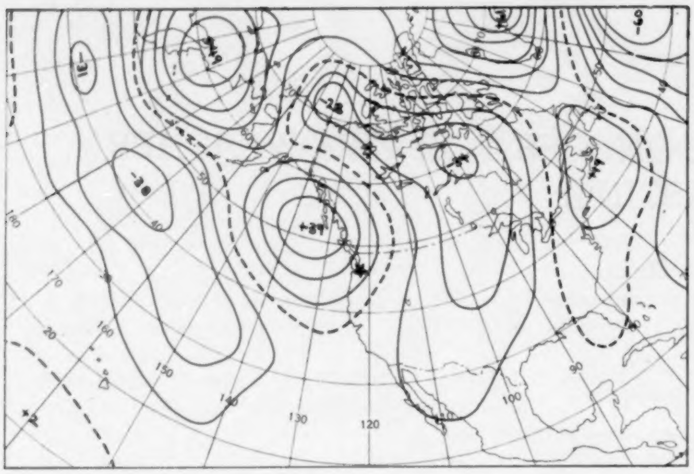

FIGURE 1.—5-day mean 700-mb. departure from normal height pattern for the period September 19–23, 1957. In this period the average 4 p.m. relative humidity over northwestern Oregon was extremely low, 20.5 percent.

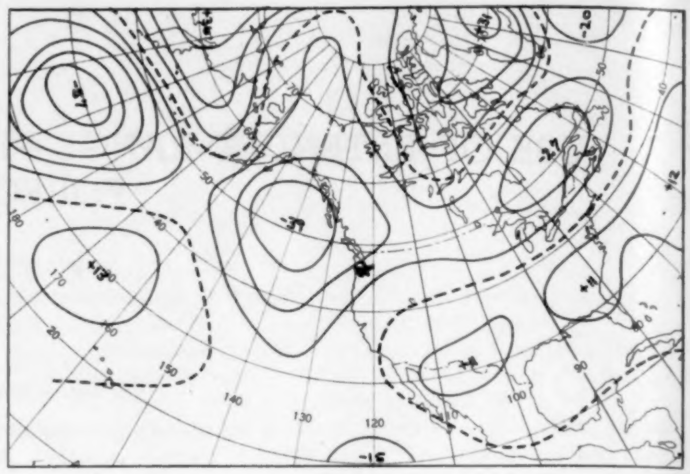

FIGURE 2.—5-day mean 700-mb. departure from normal height pattern for the period September 26–30, 1951. In this period the average 4 p.m. relative humidity over northwestern Oregon was extremely high, 64.4 percent.

typical of all the warm dry periods with strong east winds over northwestern Oregon.

The departures from normal of the 700-mb. heights for the period of September 26–30, 1951, are shown in figure 2. The average 4:00 p.m. relative humidity was 64.4 percent for this period, one of the more moist periods during the 10 years of data. This shows a strong negative departure from normal in the same general area as that of the positive departure in figure 1, which indicates the tendency for troughs of cool, moist air to persist over the Gulf of Alaska.

The presence of a positive departure from normal in the dry periods and a negative departure from normal in the wet periods was noted in nearly all of the 98 5-day periods during the 10 years. There was, however, considerable variation in the exact location and the magnitude of the departure from normal center in the different periods.

While the departure from normal charts are very convenient and useful in the study of the meteorological conditions associated with the wet and dry periods, these charts are not included along with the regular extended forecasts and are not readily available to the field forecaster. Therefore the information obtained from the study of the departure from normal charts was interpreted in terms of 5-day mean 700-mb. circulation charts. Many different 700-mb. heights, height gradients, and other variables were tried, but the best results were obtained using the parameters shown in figure 3. The vertical coordinate is the 700-mb. 5-day mean height value just off the coast (actually at 45° N., 125° W.). The horizontal coordinate is a measure of the pressure-height gradient between this point and the interior, actually the mean of the height gradients from 45° N., 125° W. to 50° N., 115° W. and from 45° N., 125° W. to 40° N., 120° W.

The numerical entries on the scatter diagram are the average 5-day relative humidities at the three selected stations in northwestern Oregon. The entire set of 98 5-day periods represented on this scatter diagram were then divided into the five classes: A, B, C, D, and E with the average relative humidity increasing from A to E. One-quarter of all cases occurs in each of the three middle groups and one-eighth of the cases in each of the extreme classes.

A careful search was made for other parameters in the 5-day mean prognostic material sent to the field forecasters that would be useful in forecasting the relative humidities in northwestern Oregon. Many such parameters were tested and had to be abandoned because valid relationships could not be established. However, it was found that the observed 5-day temperature and precipitation anomalies for northwestern Oregon each had a good correlation with the relative humidity in that area. The temperature anomaly was selected, as it was felt that the forecasting skill for this feature is a little better than in the case of precipitation.

A new scatter diagram, shown in figure 4, combines the results from the circulation patterns and the temperature anomalies. The vertical coordinate includes the standard temperature anomaly classes: much above, above, normal, below normal, much below normal. The four intermediate classes, such as much above to above, were included because more than one anomaly class may be present over the area of northwestern Oregon. The horizontal coordinate in this scatter diagram comprises the humidity classes taken from the previous scatter diagram. A dividing line was drawn as shown in the figure to best separate the low and high relative humidity periods. This line corresponds to an average 5-day relative humidity of 40 percent. This division is a fairly practical one, since the closing down of many operations and certain insurance regulations are based on a critical relative humidity of 30

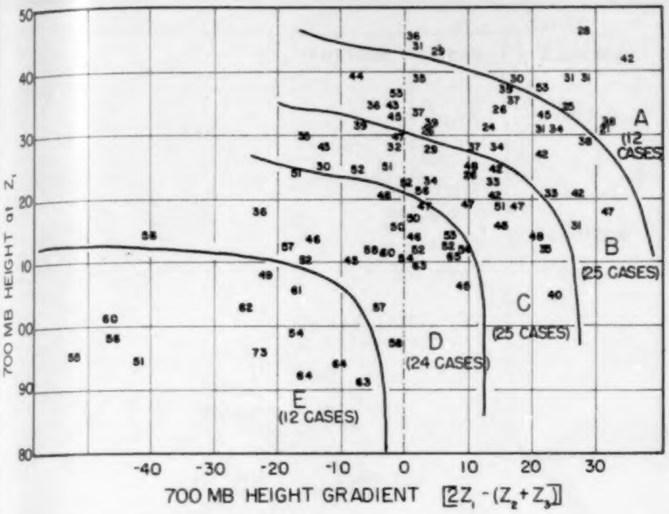

FIGURE 3.—Scatter diagram showing 5-day average 4 p.m. relative humidities for northwestern Oregon in relation to 5-day mean 700-mb. heights and an average 5-day mean 700-mb. height gradient.

percent. Any 5-day period with an average of 40 percent will usually have some days with 30 percent or lower.

Using the two graphs (figs. 3 and 4) with the 10 years of observed 5-day mean 700-mb. height, height gradient, and temperature anomaly data, the contingency table shown in table 1A was constructed. Actual 5-day average relative humidities at the same three selected stations of less than 40 percent verified the dry period forecasts and 40 percent or more verified the moist period forecasts.

TABLE 1.—*Contingency table for dry and moist 5-day periods for September*

A. Using 5-day mean maps, 1949–58

	Expected			
Observed	Dry	Moist	Total	
Dry	27	10	37	
Moist	12	49	61	Skill score=0.53
Total	39	59	76/98	

B. Using prognostic 5-day mean maps 1949–58

	Expected			
Observed	Dry	Moist	Total	
Dry	23	13	36	
Moist	19	42	61	Skill score=0.32
Total	42	55	65/97	

C. Using prognostic 5-day mean maps 1954–58

	Expected			
Observed	Dry	Moist	Total	
Dry	13	6	19	
Moist	9	28	37	Skill score=0.42
Total	22	34	41/56	

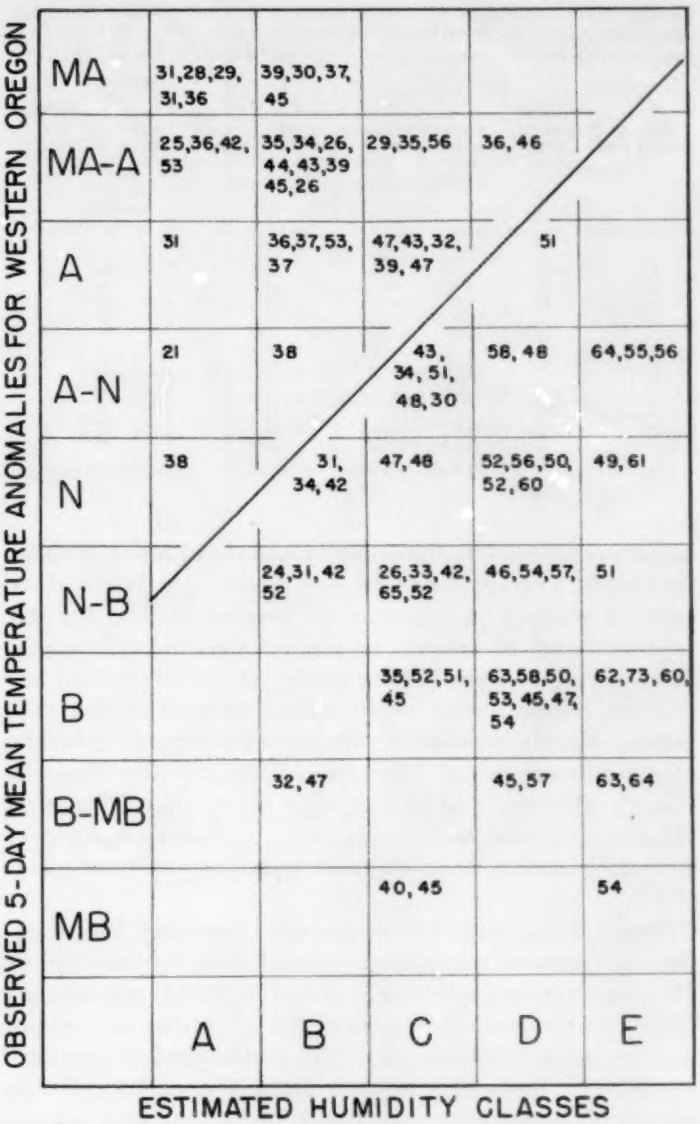

FIGURE 4.—Scatter diagram for the 5-day average 4 p.m. relative humidities for northwestern Oregon. Abscissa is the estimated humidity class from figure 3 and the ordinate, the observed 5-day mean temperature anomaly.

The system proved to be 77 percent correct in separating the dry and moist periods. A skill score based on chance, using the actual marginal totals of forecast and observed data shows 0.53 [2].

When the prognostic 5-day mean 700-mb. height and height gradient data and the prognostic temperature anomalies for the same test period were used, the correct score was reduced to 67 percent and the skill score was reduced to 0.32 (table 1B). Similar computations were made using the prognostic material for the last 5 years of this same period, 1954 through 1958. These showed a correct score of 73 percent or a skill score of 0.42 (table 1C). This suggests that the skill in preparing the temperature anomalies has improved in recent years.

The above forecast system was tested during September 1959, which was not included in the original sample. The

TABLE 2.—*Verification of 5-day average 4 p.m. relative humidity forecasts for September 1959*

Forecast period 1959	Prognostic humidity class from fig. 3	Prognostic temperature anomaly	Objective relative humidity forecast from fig. 4	Observed mean relative humidity (percent)	Verification of objective forecast	Subjective forecast in terms of chance of strong east winds (percent)	Verification of subjective forecast
9/1- 5	C	N	Moist	57	+	20	+
9/3- 7	C	A-N	Moist	69	+	40	+
9/5- 9	E	N-B	Moist	55	+	10	+
9/8- 12	B	B	Moist	41	+	30	+
9/10-14	D	B	Moist	47	+	20	+
9/12-16	E	A-N	Moist	54	+	30	+
9/15-19	E	A-N	Moist	63	+	10	+
9/17-21	E	N-B	Moist	65	+	20	+
9/19-23	E	B	Moist	61	+	20	+
9/22-26	D	B	Moist	61	+	70	−
9/24-28	C	A	Dry	61	−	60	−
9/26-30	C	B	Moist	51	+	30	+
9/29-10/3	A	B	Moist	45	+	80	−

basic forecasts are in terms of dry and moist 5-day periods. As before, average 5-day relative humidities at the three selected stations of less than 40 percent verified the dry forecasts and 40 percent or greater the moist forecasts. However, it was pointed out earlier in the article that low relative humidities in northwestern Oregon during September almost invariably coincide with periods of strong east winds across the Cascades. Thus, the dry forecasts can be interpreted as periods with better than 50 percent chance of strong east winds and the moist forecasts as periods with less than 50 percent chance of strong east winds.

Before being issued as operational forecasts, the objective forecasts in some cases were altered subjectively by the fire-weather forecaster. Also the final forecasts were issued in terms of the probabilities of strong east winds. In two cases, when the objective method called for moist conditions, more recent data from the eastern Pacific appeared to increase the chance of east winds, and the objective forecast was changed subjectively to indicate a greater than 50 percent chance of dry, east winds. In both cases, the objective prediction proved to be accurate and the east winds or low relative humidites did not develop.

The thirteen 5-day forecast periods which fell, all or in part, in September were considered in the verification (see table 2). Of the 13 subjective forecasts issued, low relative humidities (or greater than 50 percent chance of strong east winds) were forecast 3 times and high relative humidities (or less than 50 percent chance of strong east winds) were forecast 10 times. The month of September 1959 was quite unusual in that there were no low relative humidity or strong east wind conditions. Thus, the forecasts verified 10 out of 13 times.

It is interesting to note that the objective forecast would have resulted in 12 correct forecasts out of 13 cases. Statistically, neither result can, of course, be considered as showing any real basis for forecasting skill because (a) no strong east wind or low relative humidity periods were observed and (b) the number of forecasts is too small.

FIGURE 5.—The ten National Forests in the western portion of U.S. Forest Service Region 1.

It is believed that extended forecasts of periods of warm dry weather and continental winds, such as the east winds in Oregon and Washington, the Santa Anas in southern California, the "monos" in northern and central California, and northwesterly winds in southeastern United States, are feasible and can be related to the development of a persistent and intense upper ridge on the 5-day mean charts. This piling up of warm dry air probably takes place immediately upstream from the forecast area. Much work will have to be done in determining the proper parameters to be used in each of these cases.

3. THUNDERSTORM OCCURRENCES IN NORTHERN ROCKY MOUNTAINS

In the northern Rocky Mountains, thunderstorms and lightning fires create a major forest fire hazard. These storms occur during July and August when the fuels are either dry or are drying out rapidly. Many of these thunderstorms have little or no precipitation reaching the ground. Over 70 percent of all the fires in Forest Service Region 1, comprising Montana, northern Idaho, and extreme northeastern Washington, are caused by lightning. During one extreme 10-day period in 1940, 1,488 lightning fires were started. It is essential from a fire control standpoint to anticipate this lightning fire hazard. Considerable success has been achieved in the 24- to 48-hour forecasts, but little attention has been given to the forecasting of thunderstorms on a 5-day basis.

The purpose of this part of the study is to correlate certain meteorological variables which appear on the 5-day mean charts with thunderstorm occurrences in the

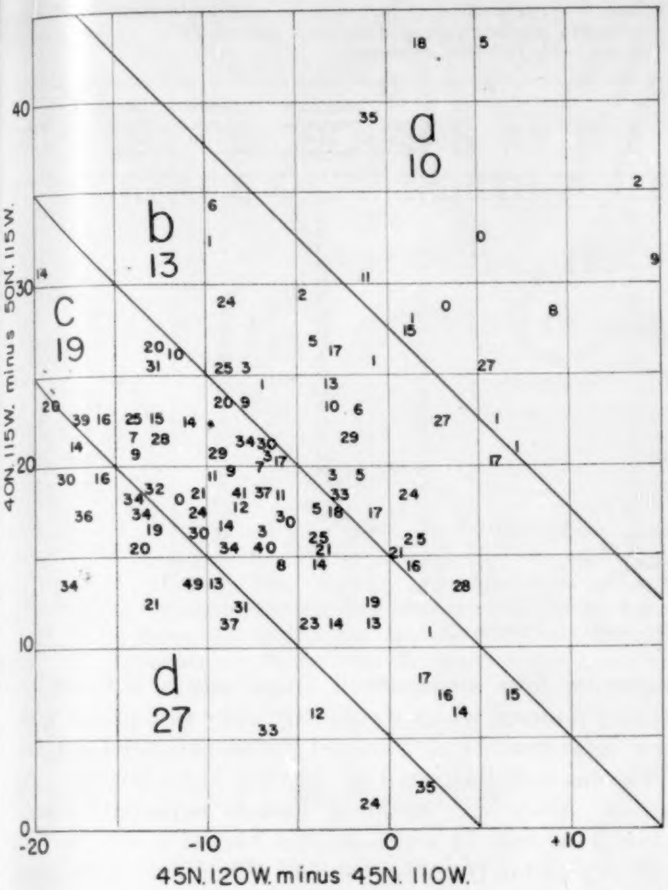

FIGURE 6.—Scatter diagram for National Forest-thunderstorm days using the 5-day mean 700-mb. west-east and north-south height gradients as the parameters.

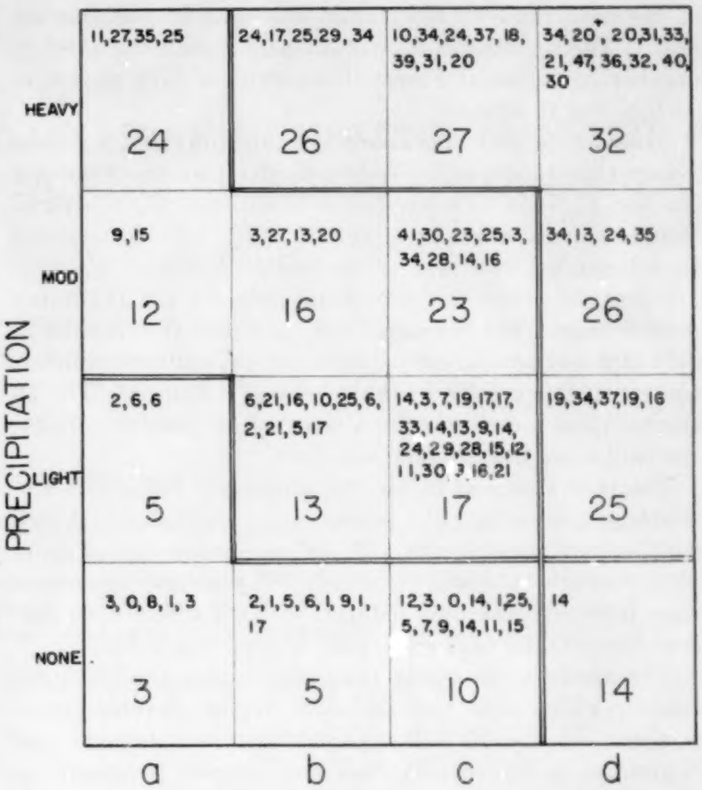

FIGURE 7.—Scatter diagram for National Forest-thunderstorm days. Abscissas are the estimated classes from figure 6 and the ordinates are the 5-day observed precipitation anomalies.

northern Rocky Mountains. In the 10 National Forests in the western portion of Forest Service Region 1, shown by figure 5, the occurrence of thunderstorms by National Forests was tabulated for the 5-day periods coinciding with those used by the Extended Forecast Section. This included 112 periods, mostly in July and August, from 1954 through 1958. If a thunderstorm was reported anywhere in a National Forest, this was listed as a thunderstorm day for that Forest. Thus over any 5-day period, the number of National Forest-thunderstorm days could vary from 0 to 50.

After a careful inspection of the observed 5-day mean departure from normal charts and the observed 5-day mean circulation patterns at both the surface and 700-mb. levels, several parameters were tried in an effort to find some correlation with the observed number of National Forest-thunderstorm days. The 700-mb. heights at various significant points in the immediate or adjacent areas, the vorticity over the area as determined from the 700-mb. height data, and various height gradients were tried.

The most useful parameters proved to be the west-east (45° N., 120° W.–45° N., 110° W.) and the south-north (40° N., 115° W.–50° N., 115° W.) height gradients on the observed 700-mb. 5-day mean charts. This is reasonable since flow from the southerly quadrant should be more effective in bringing in the necessary moisture for thunderstorm initiation than flow from the northwest or north.

A scatter diagram (fig. 6) was constructed using the west-east and south-north height gradients as the predictors with the actual number of National Forest-thunderstorm days plotted at each point. While there is considerable scatter in the number of thunderstorm days within each division, it was possible to stratify the data into four classes, a, b, c, and d, with averages of 10, 13, 19, and 27 National Forest-thunderstorm days respectively in each class.

Additional parameters were sought, including 5-day temperature and precipitation anomalies. There proved to be little correlation with the temperature anomalies, but the precipitation anomalies were well correlated with the number of thunderstorm days. While precipitation is in a degree dependent on the circulation patterns, it is also dependent on other meteorological processes, such as vertical motions and availability of moisture.

The final scatter diagram (fig. 7) was constructed by using the class intervals obtained from figure 6 and the observed precipitation anomalies as the predictors. Four classes were used in the precipitation anomaly data: I. None; II. None to light and light; III. Light to moderate and moderate; IV. Moderate to heavy and heavy. The intermediate classes were necessary because

of the occurrence of more than one class in the forecast area. The results are shown in figure 7 with the average number of National Forest-thunderstorm days shown in each of the 16 squares.

In order to test the above relationship, the National Forest-thunderstorm days were divided into the following classes: I. None to a few (10 or less days); II. Scattered thunderstorms over area (11 to 24); III. Widespread thunderstorms over area (25 or more).

Using the entire developmental data for the 112 5-day periods from 1954 through 1958, covering the months of July and August and extending a few days into September, the contingency table in table 3A was obtained. The 66 correct class forecasts gave a score of 59 percent correct; the skill score over chance was 0.38.

The next step was to use the prognostic 5-day 700-mb. charts and the prognostic precipitation anomalies. A new contingency table (table 3B) for the same period from 1954 through 1958 was obtained. The number of correct class forecasts was now reduced to 56, a score of 50 percent correct; the skill score over chance was 0.24.

The above system was tried out during the 1959 fire season, which was not included in the developmental sample. Of the 25 5-day periods between July 11 and September 5, the correct class was forecast 16 times and misses occurred on 9 times (see table 4). However, this may not be a fair test since the period from July 11 through the first half of August was quite dry with very few thunderstorms.

It should be pointed out that these forecasts give the total number of expected thunderstorm days by National Forests over the 5-day period and not the distribution of the storms during the period. It must also be realized that in any given 5-day period an excessive number of

TABLE 3.—*National Forest-thunderstorm days over 5-day periods for July and August*

A. Using 5-day mean observed charts for 1954–58

		Observed			
		10 or less	11 to 24	25 and over	Total
Expected	10 or less	21	6	1	28
	11 to 24	12	25	14	51
	25 or over	1	12	20	33
	Total	34	43	35	66/112

Percent correct=59 Skill score over chance=0.38

B. Using 5-day mean prognostic charts for 1954–58.

		Observed			
		10 or less	11 to 24	25 or over	Total
Forecast	10 or less	18	10	15	43
	11 to 24	13	26	9	48
	25 or over	1	8	12	21
	Total	32	44	36	56/112

Percent correct=50 Skill score over chance=0.24

TABLE 4.—*Verification of National Forest-thunderstorm day forecasts by 5-day periods during July and August 1959. (I=10 or less, II=11–24, III=25 or more)*

Date	Class from fig. 6	Prognostic precipitation anomaly	Objective class forecast from fig. 7	Observed thunderstorm days	Observed Class
7/7–11	a	O–L	I	<10	I
9–13	c	O	I	3	I
11–15	c	O	I	3	I
14–18	b	O	I	0	I
16–20	c	O	I	2	I
18–22	c	O	I	2	I
21–25	b	O	I	5	I
23–27	b	O	I	12	II
25–29	c	O	I	8	I
28–8/1	b	O	I	14	II
30–8/3	a	O	I	13	II
8/1–5	c	O	I	8	I
4–8	b	L–M	II	1	I
6–10	b	O	I	0	I
8–12	b	O	I	8	I
11–15	a	M	II	8	I
13–17	a	M	II	0	I
15–19	b	M	II	9	I
18–22	a	M–H	II	27	III
20–24	b	M–H	III	26	III
22–26	c	M	II	13	II
25–29	b	L	II	14	II
27–31	a	M–H	II	17	II
29–9/2	b	H	III	5	I
9/1–5	a	O	I	3	I

16 Correct 9 Wrong

lightning fires might result from only a few scattered thunderstorms, which would only show as a period with a low total number of National Forest-thunderstorm days. This was well illustrated by the July 31 to August 1, 1959 storm. Only six National Forests reported thunderstorms on July 31 and seven on August 1 with no other activity within the 5-day period. Thus, this period shows a total of only 13 National Forest-thunderstorm days for the 5-day period even though a very large number of lightning-caused fires resulted from these storms. These storms were accompanied by little or no precipitation and the ground fuels were critically dry when the storms occurred.

This present study does not directly differentiate between thunderstorms with heavy precipitation and thunderstorms with little or no precipitation. This should be investigated more carefully in future studies.

However, it is felt that this type of extended forecast has considerable value to fire control operations. As the techniques and accuracy of the 5-day forecasts improve and further interpretative studies are made, this tool can serve as a working basis for the planning for the next 5 days. Since the 5-day forecasts are issued three times each week, major reappraisals can be made when it becomes apparent that the previous forecasts are incorrect. It is urged that similar work be done for thunderstorms in other areas.

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THE CIRCULATION AT THE 10-MILLIBAR CONSTANT PRESSURE SURFACE OVER NORTH AMERICA AND ADJACENT OCEAN AREAS

July 1957 through June 1958

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ABSTRACT

A recently published set of 10-mb. charts analyzed three times monthly, July 1957 through June 1958, is used as a basis for discussion of the high stratospheric circulation during those first 12 months of the International Geophysical Year. There is a slow, steady transition from summer easterlies to winter westerlies which appear first in high latitudes and then strengthen and expand southward. In January and February 1958, the circulation breaks down rapidly and in a highly complex manner. By May, polar easterlies become established and spread southward to merge with the intensifying subtropical easterlies.

Several related topics on the nature of medium- and large-scale developments are discussed.

1. INTRODUCTION

Recent advances in science and technology have generated a requirement for a more detailed knowledge of atmospheric circulation at increasingly high levels. Rockets and missiles regularly penetrate the 10-mb. surface (near the 31-km. level). Unmanned balloons carrying a variety of instrumentation have drifted for days near the 30-km. level, and one such balloon is known to have attained a height exceeding 45 km. At least three men have already journeyed as high as the 10-mb. surface. The late Capt. Iven C. Kincheloe reached 38 km. in a U.S. Air Force X-2 rocket aircraft on September 7, 1956; Maj. David G. Simons ascended to 31 km. in a sealed gondola carried by a 6,000,000 cu. ft. plastic balloon on August 20–21, 1957; and Capt. Joe B. Jordan flew an F-104C jet plane to 31.5 km. on December 14, 1959.

The tremendous eruption of the Krakatoa volcano on August 27, 1883 (Wexler [20]), threw material from the surface of the earth to a height of 32 km. where the dust cloud circled the earth at an average speed of 63 kt. to give evidence of equatorial easterlies at this level. More recently, debris has been cast up to the 30-km. level by hydrogen-bomb explosions. There, depending upon season and latitude, it has been carried eastward or westward around the earth in a few days. Some of this material has even drifted across the equator to fall out in the Southern Hemisphere.

What do we have in the way of reliable meteorological information about the middle layers of the stratosphere? Can ascent to these heights be made with reasonable confidence in the sort of weather and winds that may be encountered there? Prior to the International Geophysical Year these heights were frequently attained by ascents made at a score of United States military radiosonde stations scattered about the Northern Hemisphere. In addition, occasional special meteorological probes were made to 30 km. or higher. The data from such ascents were adequate for an estimate of the generalized temperature and wind distribution at 10 mb. but left unresolved many questions regarding such details as the amplitude, wavelength, and speed of perturbations at this level. Other topics requiring more accurate data for greater understanding are related to the vertical structure, development, and maximum strength of the wintertime Arctic stratospheric jet stream (or "Astrajet" as we shall call it here) and to the phase relationships between streamlines and isotherms during progression, retrogression, and rapid development of disturbances in the circulation of the stratosphere.

With the beginning of the International Geophysical Year, sufficient effort was placed on the attainment of great heights by routine radiosonde runs for depiction of the daily circulation at 10 mb. with reasonable accuracy over a large area. Recently, increasing numbers of observational studies (see references in this paper and in Hare [2]) have shown, in various degrees of detail, some characteristics of the circulation and climatology of the stratosphere. The Stratospheric Analysis Project of the U.S. Weather Bureau has already published [18] a set of 10-mb. charts, analyzed three times monthly for the first 12 months of IGY, July 1957 through June 1958. Analysis of additional sets of 10-mb. charts and of 30-mb.

(24 km.) charts for the same period is now in process. Another important function of this project is the analysis of daily 100-mb. (16.5 km.) and 50-mb. (20 km.) Northern Hemisphere charts for the IGY period, July 1957 through December 1958 [19].

The purpose of this paper is to describe the major features of the 10-mb. circulation and its changes in the period July 1957 through June 1958. The description is based primarily on the published set of 10-mb. charts [18] and selected charts from this set are shown in figures 2, 4–7, and 10–12.

2. PROBLEMS OF PROCESSING AND ANALYZING 10-MB. DATA

Even at best, observed 10-mb. data are scarce and extrapolated data must be depended upon as a supplement. The modest budget of the project did not permit an elaborate system of building up the 10-mb. analysis from lower levels on a routine basis by use of mean virtual temperature charts and differential analysis. Instead, individual soundings that reached nearly to the 10-mb. surface were extrapolated. In other cases, soundings were reconstructed from time-section data coupled with data from surrounding stations.

Random errors in temperature and height data are far larger at 10 mb. than at lower levels and, moreover, are superimposed upon a large systematic diurnal variation. Much of the diurnal variation is spurious, being caused by alternate solar heating and nocturnal cooling of the temperature element of the radiosonde. A great amount of instrument research will have to be performed before the exact nature of the radiation error is known for all types of radiosondes, but to reduce the difficulty of stratospheric analysis it is sufficient to use the method of Teweles and Finger [15]. This system eliminates the diurnal variation of most types of United States radiosondes used during the IGY by reducing daytime values to the level of nighttime values. The magnitudes of the temperature and height corrections applied to the 10-mb. data are shown in figure 1. The corrections shown for the duct-type instruments are in addition to corrections [17] already applied during evaluation of the raw data at the radiosonde station.

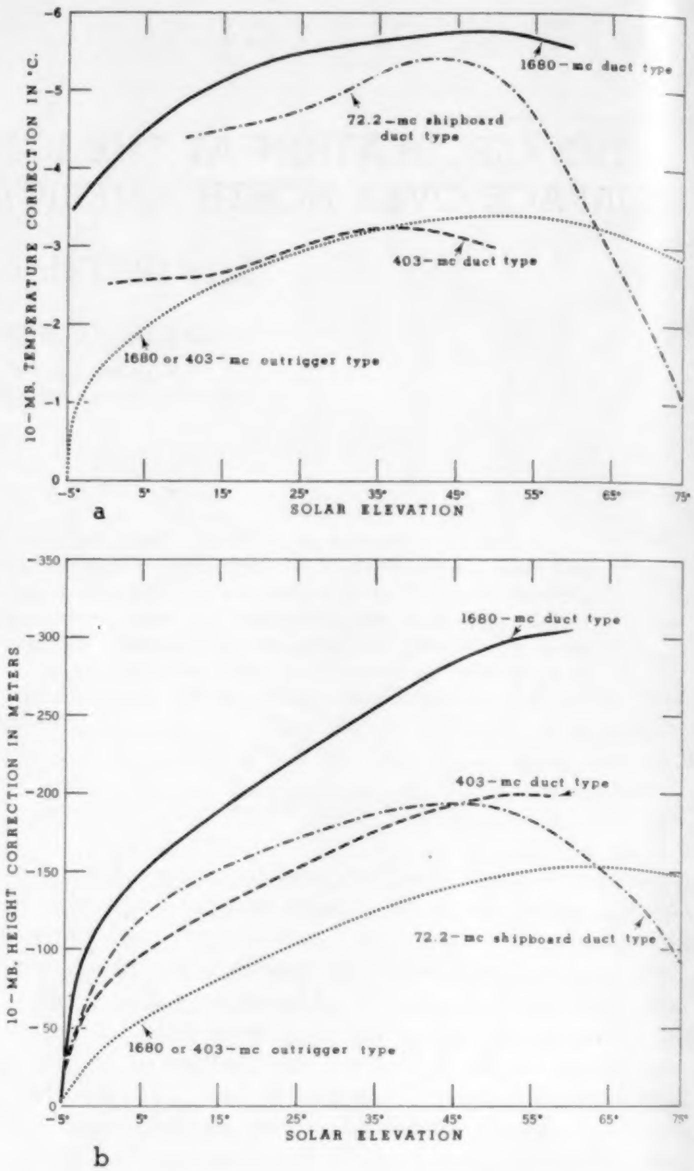

Figure 1.—Temperature (a) and height (b) corrections for use with 10-mb. data reported from the principal United States radiosondes used during the International Geophysical Year.

Radiation theory indicates that heat losses by some types of thermistors in darkness may cause reported nighttime 10-mb. temperatures to be as much as 2° C. below the true values. If this is true and there is no compensation by other effects such as stray battery heat, then the 10-mb. isotherms drawn on these charts should be labeled higher by that amount. There is evidence (Teweles and Finger [15]) that this temperature error, if it exists, does not differ much for various types of instruments and so would result in a fairly constant height error, having little effect upon the gradient of contour height. In determining the contour analysis, the wind data were found to be far more useful than the height data which, in fact, found their main use in the estimation of the values to be used in labeling the contours. Height data also had some use in the determination of the spacing of contours across large ocean or land areas having little or no wind data.

The sparsity of 10-mb. data made it necessary to utilize for the analysis not only the synoptic reports but also all other observations reaching to or nearly to the 10-mb. surface on the same day, the preceding day, or the following day. Comparison of the various reports entered at a station made it possible to discard obviously erroneous values and to interpolate between reports in order to find the most probable data at map time. In drawing contours to agree closely with the observed wind field, the analyst can give little weight to the reported

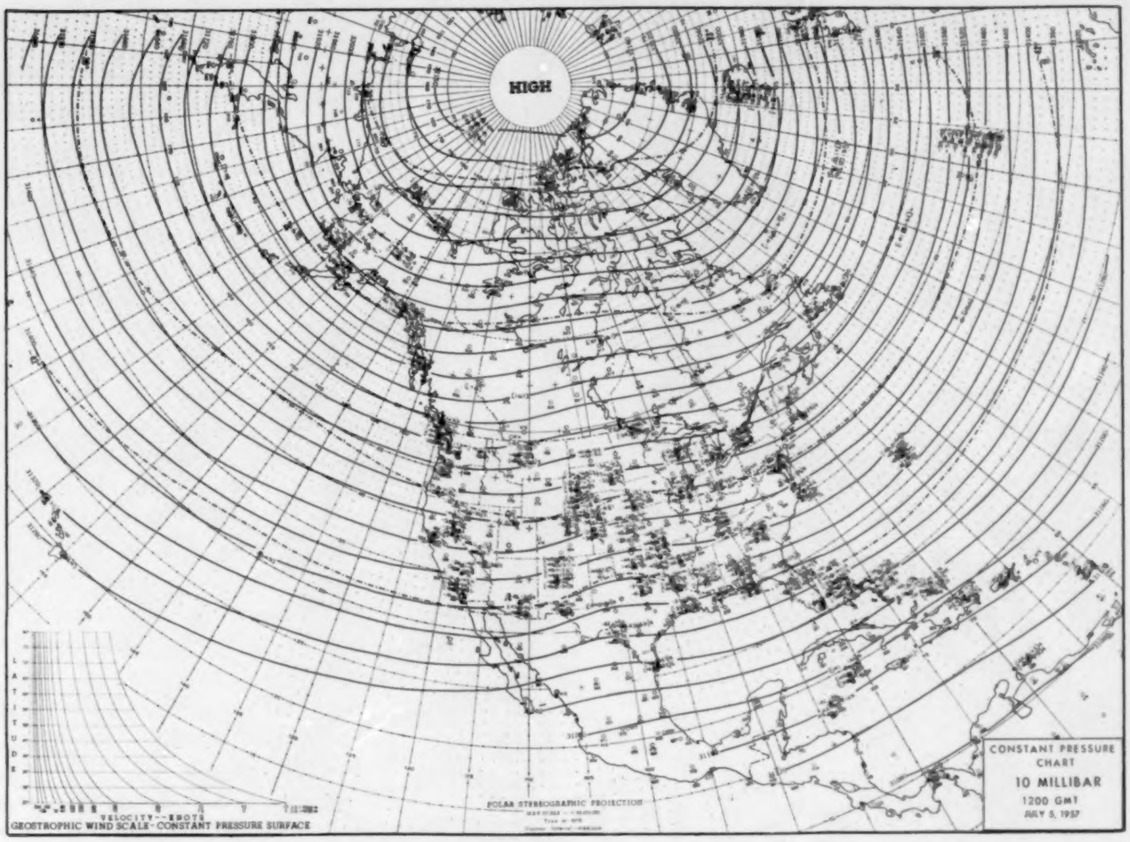

Figure 2.—The 10-mb. chart for 1200 GMT July 5, 1957, from [18]. Contours at intervals of 40m., isotherms (dot-dash lines) at intervals of 3° C.

heights. Furthermore, the analyst has little in the way of synoptic models for guidance with respect to probable contour and isotherm patterns or the phase relationship between them. Thus, the amount of subjectivity in the 10-mb. analysis is much greater than that found in the analysis of tropospheric charts. In spite of these factors, surprisingly little modification of the principal features of the circulation and temperature distribution shown in the final analyses is possible without disregarding more data than are better satisfied by the change.

Large-scale patterns with wavelength of the order of 6,000 km. are quite accurately shown by these analyses, and some medium-scale features have been revealed by conscientious efforts to detect and delineate them. Frequently, however, when their amplitudes are small these medium-scale perturbations tend to be obscured by the large observational errors. Nevertheless these 10-mb. charts serve a useful purpose by portraying important features of large-scale circulation changes for comparison with analogous changes at lower levels. Moreover, with these charts to act as a foundation, activity at still higher levels can be estimated, particularly if supplemental data from a few high-reaching balloon or rocket soundings are available.

3. THE SUMMER EASTERLIES

(July 1957 and June 1958)

Because the reference series of maps begins with the month of July, it is necessary here to discuss the summer easterlies by combining charts for two different summers. The 10-mb. chart for July 5, 1957 (fig. 2),* shows the typical summertime contour pattern with a High centered near the pole and circumpolar easterlies at all latitudes. This circulation persisted only until the beginning of August 1957, but in the following year became reestablished by the middle of June. The summertime circulation, once established, changes very little from day to day, at least in the large-scale pattern. Careful examination of wind directions during this period suggests the existence of small amplitude perturbations in the easterlies, but in the subtropics and lower mid-latitudes, the wind directions in these perturbations deviate little more than 10 degrees on either side of straight easterly.

An interesting feature of this summertime circulation

*Figures 2, 4, 5, 6, 7, 10, 11, and 12 are reproduced, after reduction to approximately one-half size, from the U.S. Weather Bureau [18] publication, *10-millibar Synoptic Weather Maps*. In the process, the plotted data have become illegible. Institutions or research groups having need for greater detail than is found here will be furnished with a copy of the booklet, as long as the supply lasts, upon request to Chief, U.S. Weather Bureau Reference R-3.42, Washington 25, D.C.

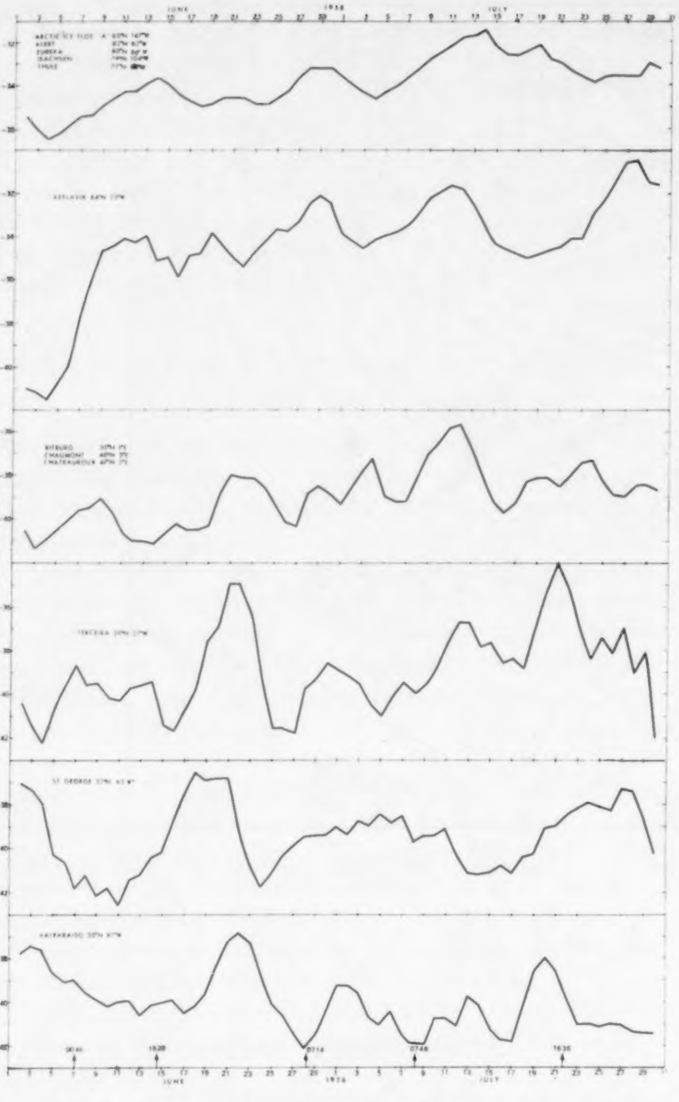

FIGURE 3.—10-mb. temperatures (3-day running means) at several stations from June–July 1958. A few individual values were extrapolated from as low as the 13-mb. level. Temperatures were adjusted to eliminate bias from radiational errors.

is the almost uniform contour gradient from the Arctic to the subtropics. This phenomenon seems to have only the trivial significance that the wind speed is inversely proportional to the sine of the latitude. The observed decrease of wind with latitude suggests solid rotation, but this would require the wind speed to vary with the cosine of the latitude with the greatest horizontal wind shear in the high latitudes instead of the lower mid-latitudes as observed.

The isotherm patterns suggest that, due to the influence of 24-hour radiation from the sun, the Arctic warms more rapidly than the areas south of the Arctic Circle. The areas of residual coolness in middle latitudes melt away during the month of June and appear to be absent by mid-summer when the isotherm pattern becomes nearly circumpolar without isolated closed centers.

Details of the early summer isotherm patterns are obscured by the large temperature errors charcteristic of 10-mb. data. These errors are frequently as large as the day-to-day temperature changes and in summer are equal to the horizontal temperature difference across a very wide area. The isotherm pattern may be overly smoothed since the analyst did not have the means to make a detailed analysis of the temperature variation at individual stations and thus may occasionally have disregarded an unusual but correct value.

Determining the reality of small temperature changes reported at 10 mb. is a difficult problem for the analyst. The magnitude of the changes he must recognize is indicated in figure 3 by 3-day running means of 10-mb. temperatures in areas where there are several nearby stations, or at stations where observations are taken four times daily. The period of the changes is roughly 10 to 15 days. Their magnitude increases from about 4° C. in the Arctic to 7° C. in middle latitudes, but seems to decrease again at lower latitudes. Of course, the real changes are somewhat larger than those of the 3-day running means and, in addition, random errors have been greatly reduced by this averaging process. The curves of figure 3 show minor 10-mb. temperature variations ranging from 2° or 3° C. near the pole to 5° or 6° C. at 30° N. Since the atmosphere at 10 mb. in summer is statically quite stable, vertical motion of only one-half kilometer would produce sufficient adiabatic heating or cooling to explain these observed temperature changes of only 5° or 6° C.

Scherhag [11] has already discussed the Berlin 20-mb. and Bitburg 25-mb. temperature changes over Germany during this period (June–July 1958). Random errors in the data were subdued by preparing 5-day running means of observed temperatures. He remarks that a solar eruption occurred at 0400 GMT, July 7 and after the interval required for solar particles to reach the earth from such a disturbance, an extraordinarily strong terrestrial magnetic and ionospheric storm was observed on July 8. According to Scherhag, such temporal relationships between solar eruptions, magnetic and ionospheric storms, and sudden warmings of the stratosphere are not accidental.

The temperature changes shown in Scherhag's paper are comparable in size with those in the 10-mb. temperatures shown here (fig. 3). The temperature rise, following the sudden commencement of the ionospheric disturbance at 0748 GMT July 8 can be observed not only in western Europe but also over the Atlantic Ocean at Terceira and Keflavik and less markedly over the Arctic. St. George and Valparaiso temperatures at this time show no definite response. Over these latter stations and at Terceira more pronounced and relatively simultaneous temperature peaks occurred from June 18 to 22. Other sudden commencement dates given in an article by Williams [23] are indicated in figure 3 but heralded much weaker ionospheric disturbances (U.S. National Bureau of Standards [16]) than that of July 8. For this reason and because it occurred so early, the sudden commencement of June 14

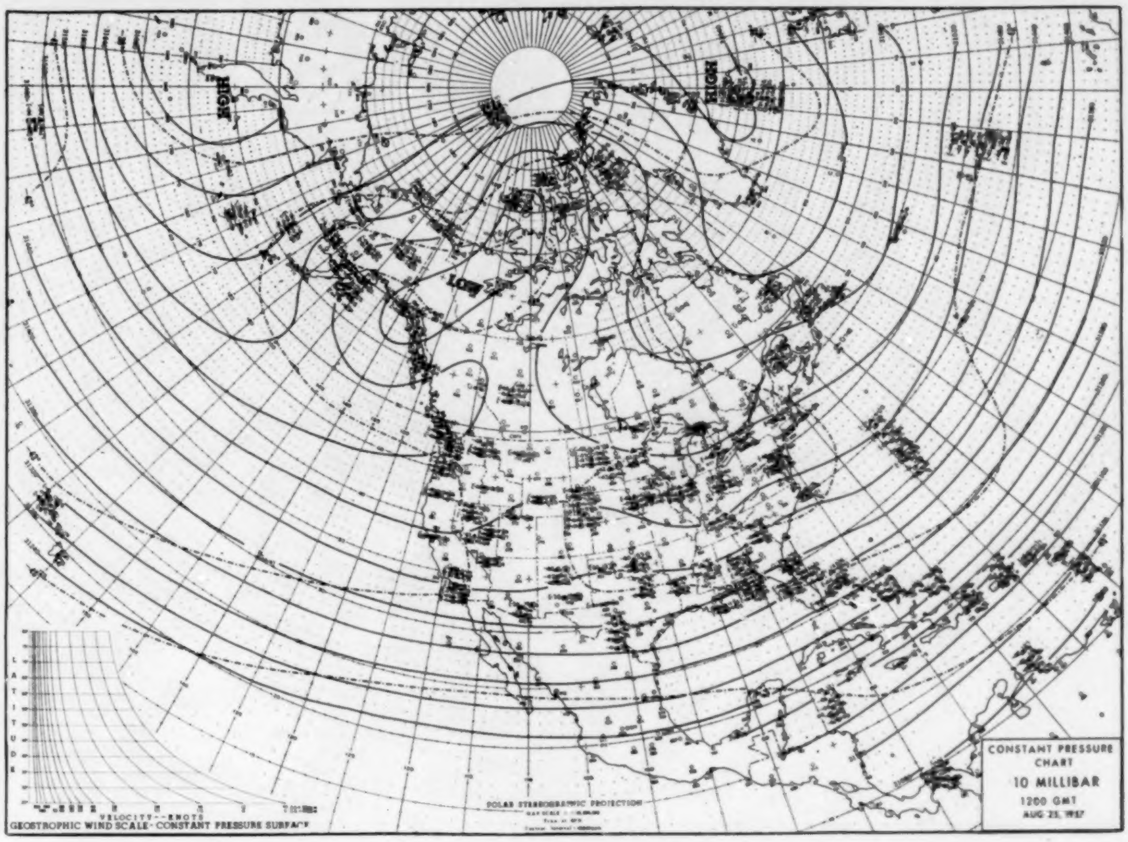

FIGURE 4.—The 10-mb. chart for 1200 GMT August 25, 1957 from [18]. Contours and isotherms as in figure 2.

hardly seems capable of explaining the June 18 to 22 warmings. A careful investigation of the changes of 10-mb. circulation associated with these changes of 10-mb. temperature is highly desirable but requires painstaking study beyond the scope of this paper.

4. TERMINATION OF THE REIGN OF THE EASTERLIES

(August and September 1957)

In the first half of August 1957, the high-latitude easterlies at 10 mb. began to buckle and slowly break over into westerlies. By August 25 (fig. 4), a closed circulation had developed over the Yukon Valley. North of the 45th parallel only very weak easterlies remained and meridional flow was as prevalent as zonal flow. Within the next 10 days a radical change in the position of the lowest pressure took place. Although a trough remained in western Canada, a change to northerly winds at Thule in northwestern Greenland shows that the heights had dropped more rapidly to the east of Greenland than over the North American Arctic. The general decrease in height of the pressure surface is a logical manifestation of the shrinkage of the polar atmosphere as a result of seasonal cooling. However, part of the decrease was accompanied by westward movements of the low center since the wind at Thule switched to southerly by mid-September. By the end of September the deepening trough had taken a central position in Canada and extended its influence southward to the Western Plains of the United States.

The ridge separating the still strong subtropical easterlies from the expanding ring of polar westerlies was first well-marked in early September along the 45th parallel. By late September, the ridge had migrated a full 10° of latitude southward, and the speed of the subtropical easterlies had generally fallen below 50 kt. Meanwhile the temperature at the pole fell some 20° C. from its summertime peak.

At 10 mb. in high latitudes during September and October the atmosphere cools at the rate of about 15° C. a month, suggesting a strong tendency toward radiative equilibrium. The parallelism of contours and isotherms is a generally reliable indication that there is little or no vertical transport of heat at this time. There may still be sinking motion to compensate for the cooling and shrinking of the polar layers. Furthermore, the gradual acceleration of the zonal flow requires an inflow across contours toward the pole. This inflow must be more than compensated by outflow at another level to permit the continued lowering of the pressure surfaces. Sinking of the air with outflow at lower levels provides the most logical explanation. Radiational cooling must then be called upon both to compensate for the adiabatic heating and to explain the decrease in temperature.

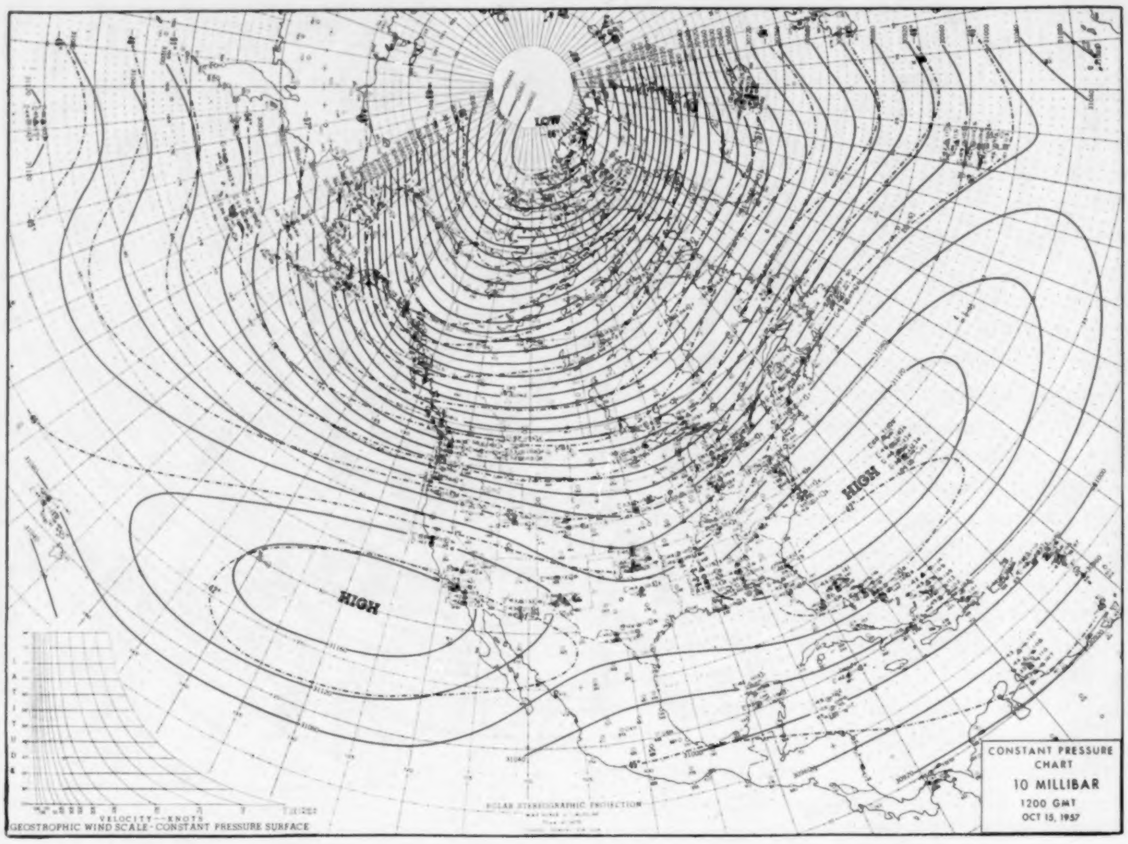

Figure 5.—The 10-mb. chart for 1200 GMT October 15, 1957, from [18]. Contours and isotherms as in figure 2.

5. THE INCREASING WESTERLIES

(October to mid-November 1957)

During October 1957, the cooling and lowering of stratospheric pressure surfaces and increase of westerly wind speeds in the high latitudes continued at an accelerated pace. As the polar temperature dropped 18° C. from September 25 to October 25, the 10-mb. surface at the pole sank one full kilometer just as it did during the previous month. In just 10 days preceding October 15 (fig. 5) temperatures over the Yukon basin dropped 8° C. or more with corresponding height falls of more than one-half kilometer. During the next 10 days, the trough line moved eastward to a position over Greenland where heights fell 700 meters and temperatures 12° C. in 10 days. These latter decreases seem to involve dynamic as well as radiational cooling.

The westerly circulation during the period from early October to early November came as close to being circumpolar as at any other time during the 1957–58 cold season. Even so there was a notable tendency in the autumn toward eccentricity of the pattern with the principal low center displaced toward the European side of the pole. This eccentricity is closely associated with the persistent tendency toward anticyclogenesis in the stratosphere over the Aleutian area.

One theory for explaining the existence of this climatological feature is that the center of the circulation is displaced from the North Pole due to enhanced radiative heat losses over the "cold poles" of Greenland and northern Siberia. By the same logic, the center is thrust away from the Aleutian area where the ocean surface is abnormally warm for that latitude. This explanation is discounted by Wexler and Moreland [22]. Its weakness is that small differences in long-wave radiation could not hold isotherms stationary in the face of advective temperature effects that often are larger by two orders of magnitude.

Another explanation, given in an earlier paper (Teweles [13]) places the energy source in the tropospheric jet stream that normally passes over Japan in winter, then spreads out, and weakens over the Pacific. This feature is strikingly illustrated by charts of the mean 300-mb. wind, temperature, and kinetic energy distribution over the Northern Hemisphere produced by Lahey et al. [3]. These charts show that between October and November and again between November and December there are marked increases in the mean strength of the jet stream over Japan. This portion of the jet stream remains at peak strength through February. Although the weaker jet stream of September and October loses little of its speed while crossing the Pacific, the jet stream during the months when its kinetic energy over Japan is greatest loses from one-half to three-quarters of its energy by the time it crosses the North American coastline. In the region surrounding the decelerating current, the conversion of kinetic energy into potential energy requires an

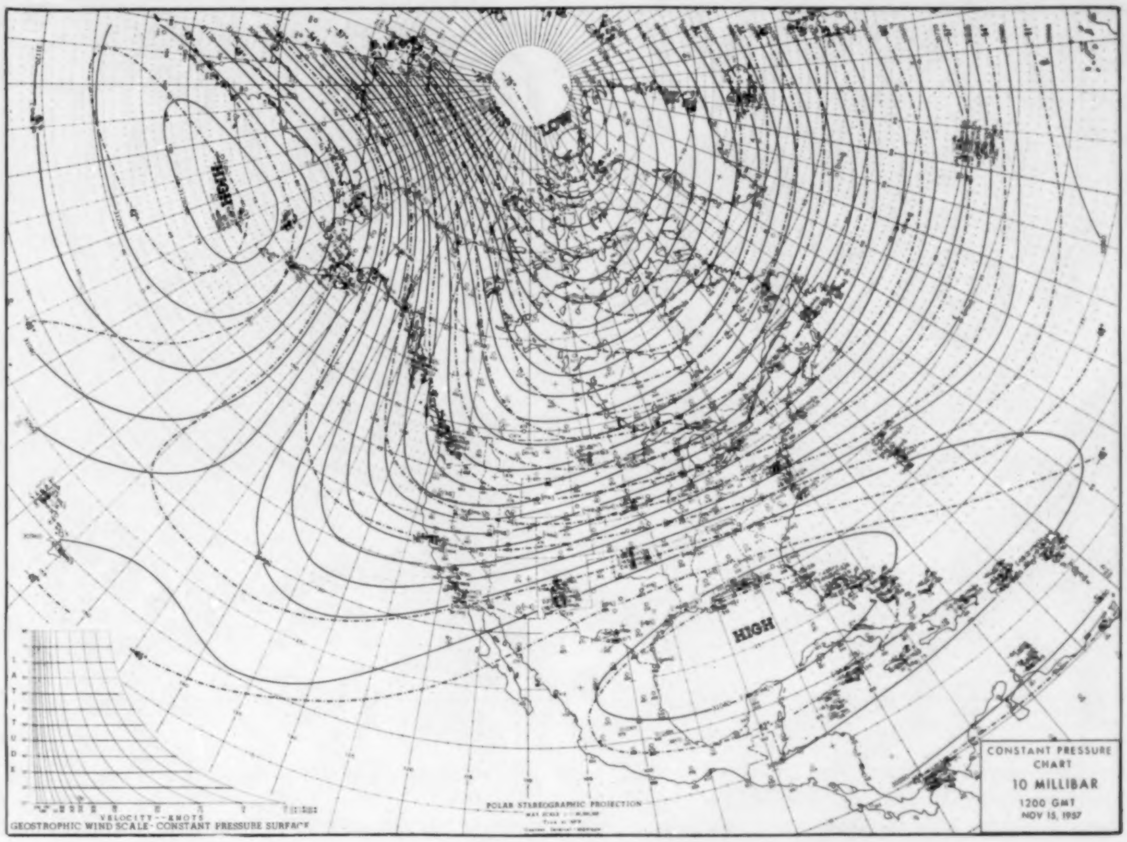

Figure 6.—The 10-mb. chart for 1200 GMT November 15, 1957, from [18]. Contour interval 80 m.; isotherm interval 3° C.

arrangement of vertical motions over the Pacific that is to be expected around an exit zone as discussed by Scherhag [10]. This explanation requires that the decelerating tropospheric westerly jet stream, bearing to the right or southward toward high pressure, will tend over most of the cold season to evacuate the layers near the tropopause level over the Aleutians. The net sinking motion above that level will produce stratospheric temperatures high for that latitude. Convergence and inflow at the high levels will maintain a strongly baroclinic region by packing isotherms between this warm air and the body of cold air produced within the Arctic Circle. The Astrajet must intensify with height to extremely high velocities in obedience with the thermal wind equation. High pressure is built up in the warm Aleutian stratosphere to produce the necessary balancing pressure gradient. This current then carves out a path of constant absolute vorticity for itself southeastward across Canada. In this explanation, the proposed cause, the tropospheric jet stream, transports sufficient energy to explain the vertical motions necessary to hold the existing field of stratospheric isotherms stationary in the face of the strong advective tendency. The generation of an indirect circulation in the region downstream from a jet stream wind maximum is discussed in greater detail by Riehl and Teweles [8].

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6. A PULSATION OF THE ALEUTIAN HIGH

(Mid-November 1957 to early January 1958)

On November 15 (fig. 6) the most noteworthy feature of the 10-mb. chart was the extensive anticyclone centered over the Aleutian Islands. This warm anticyclone had built up quite rapidly and was influencing the circulation over the entire North Pacific Ocean. The 10-mb. temperatures over the Aleutians were 25° C. or more warmer than at the same latitude over the interior of Canada. Computed heights and extrapolated winds give evidence of 150-kt. speeds in the wind current which curved clockwise from northeastern Siberia across the Arctic Ocean and Alaska into the Gulf of Alaska.

With the buildup of the anticyclone over the Aleutians there was extensive segmentation of the subtropical high pressure belt that prior to October 15 (fig. 5) and until early November was fairly continuous along 30° N. latitude. This belt as long as it remained continuous tended to isolate the subtropical easterlies from the mid-latitude westerlies. After the break up, as indicated in figure 6 by the circulation in the vicinity of both Hawaii and Mexico, large amounts of air from the deep Tropics were able to penetrate northward and mix with the polar currents. This may be a general feature of the circulation for it was at just this time of the year 1883 that the first

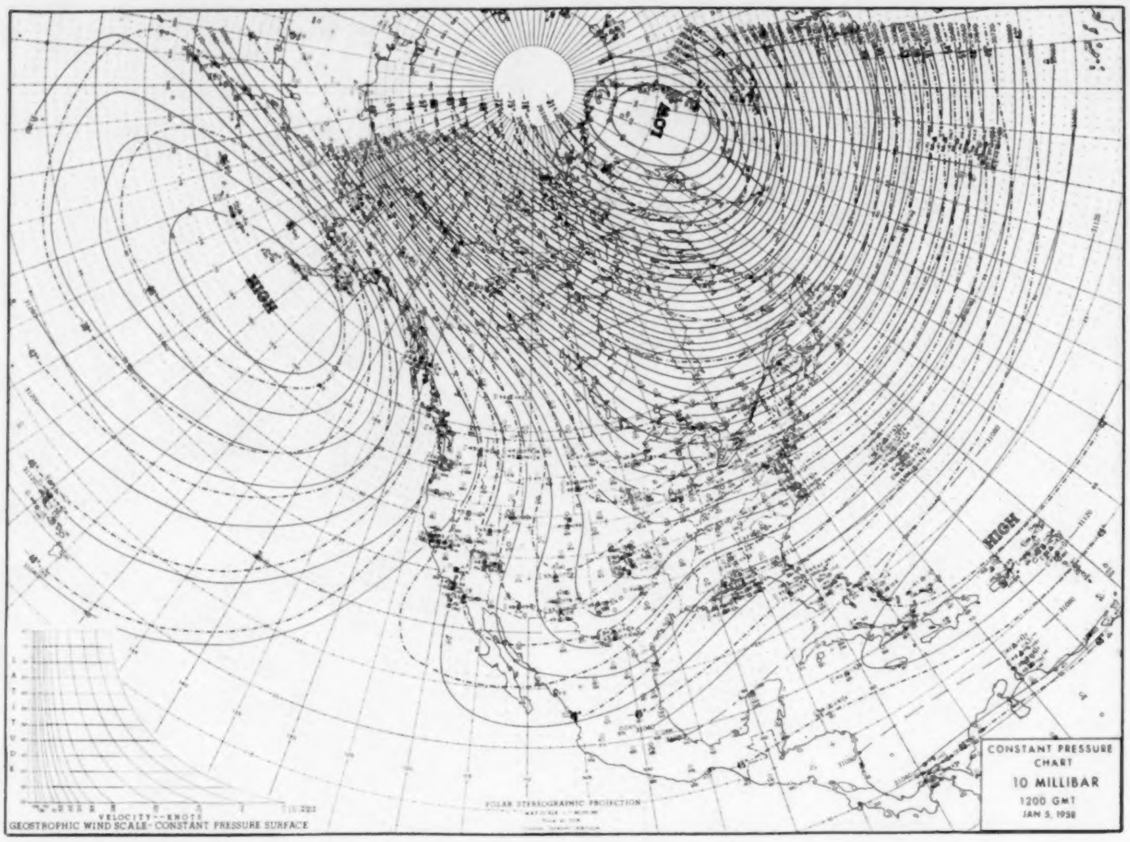

Figure 7.—The 10-mb. chart for 1200 GMT January 5, 1958, from [18]. Contour interval 80 m.; isotherm interval 3° C.

evidence of the Krakatoa dust cloud was reported in mid-latitudes (Wexler [20]). The cloud had slowly worked its way northward during September and October from its origin at 6° S., 105° E. We may presume that in 1883 as in 1957 the high pressure belt was slowly pressed southward toward the subtropics. As the two phenomena crossed, the dust cloud was carried away in the westerlies.

By late November 1957, the highest portion of the 10-mb. surface had retrogressed southwestward to a position just east of Japan. Along with the decrease in height of the 10-mb. surface over Alaska, temperatures plunged as much as 20° C. This cooling of the western portion of a trough during the retrogression of stratospheric systems was also noted as a feature of the circulation breakdown of January–February 1957 (Teweles [13]).

The westerly circulation in high latitudes by late November had again become nearly circumpolar with the lowest portion of the 10-mb. surface close to the North Pole. Flat waves, two or three in number, apparently existed in this circulation for, in addition to the Pacific ridge, another is delineated near the British Isles by southerly wind components over the Atlantic and northerly components over western Europe.

During most of December there were no major changes in the pattern, except for a slight filling of the polar low center and an irregular eastward movement of the 10-mb. systems. A remarkable change took place about the beginning of the new year, for on January 5, 1958 (fig. 7), a great ridge again occupied the stratosphere over the Aleutians. In its broad features, the circulation closely resembles that for November 15 (fig. 6). Several important differences should be noted, for they may be significant in determining the far different sequence of events that follows these situations. On November 15 (fig. 6), the height difference between Aleutian High and Arctic Low was a little more than 2 km., but on January 5, the difference was more than 3½ km. Consequently the wind current between centers was much stronger and the area of strong winds extended farther downstream on the latter date. Over the northern Atlantic, reported wind speeds doubled to more than 100 kt. between the two dates. Over Alaska and Canada, low temperatures, high winds, and scarcity of special high-flight balloons combined to prevent wind observations to great heights. However, the contour gradient requires geostrophic winds of 200 kt. over Alaska and 100 to 200 kt. southeastward across Canada.

The isotherm-contour relationship over Alaska and western Canada also differs markedly on these charts. There was little cross-isotherm flow on November 15, but on January 5 horizontal thermal advection of as much as 3° C./hr. was indicated. Since there can be little movement of isotherms in the face of 100- to 200-kt. winds this condition in combination with nearly isothermal lapse rates and adiabatic flow requires upward vertical motion of 3 to 5 cm./sec. over a distance of more than 2,500 km.

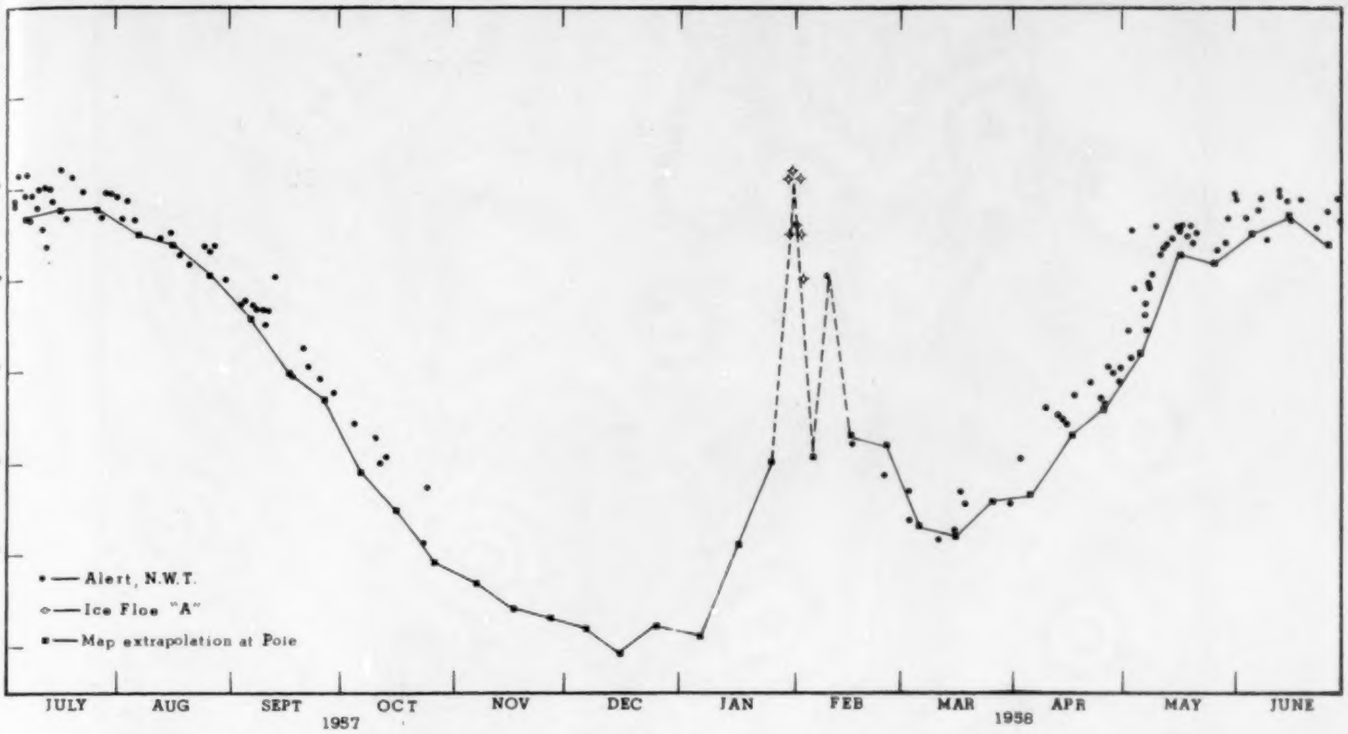

FIGURE 8.—The curve of 10-mb. temperatures extrapolated at the North Pole on each chart of [18]. All 10-mb. temperatures reported during the 12 months from Alert N.W.T. (82° N., 62°20′ W.) are included, supplemented by 10-mb. temperatures reported during January and February 1958 from Ice Floe Station "A". Daytime station temperatures are plotted from the records without reduction to nighttime values, while values extrapolated from the 10-mb. charts depend on the isotherm analysis which includes the reduction.

7. THE PERIOD OF "EXPLOSIVE WARMING"

(Mid-January to early February 1958)

In the first half of January 1958, the wavelength of the 10-mb. flow shortened as a consequence of anticyclogenesis in the Azores area while the Aleutian anticyclone held fast. Thereafter the stratospheric circulation of the Northern Hemisphere underwent a series of radical and relatively rapid changes. Some aspects of these changes observed in early 1958 have already been described in more detail elsewhere (Hare [2], Palmer [6], and Scherhag [12]). A previously published series of 25-mb. charts for January 17, 24, 28, and 29, and February 1 and 4, 1958 (Teweles and Finger [14]) shows that after January 24 the Aleutian high pressure center moved northwestward, recurved near the pole and then moved back toward its original position. Looking only at the January 24 and February 4 25-mb. charts (or the January 25 and February 5 10-mb. charts (U.S. Weather Bureau [18])), one would erroneously conclude that the anticyclone in that period had merely moved eastward a short distance. Thus, while a 10-day interval between 10-mb. charts is, during much of the year, adequate for most purposes, there are times when a daily series of charts is needed to detail sweeping changes of the 10-mb. surface as rapid as those of the troposphere.

The effect of the warming on the annual march of temperature in the polar region is vividly shown in figure 8 by temperatures observed at Alert and Ice Floe Station "A" superimposed on a graph of North Pole temperatures estimated from the entire set of 10-mb. charts (see fig. 15 of Wexler [21] for temperatures at lower levels). In the darkness of the polar night, high 10-mb. temperatures of −28° C. at 1200 GMT on January 30, 1958, and −29° C. at 1200 GMT on February 1 were reported over Ice Floe Station "A". A sharp drop in 10-mb. temperature thereafter is indicated by the 25° C. decrease in reported 20-mb. temperatures to −61° C. at 0000 GMT on February 4. A second warming occurred with a peak of about −40° C. at 10 mb. on February 10 and was itself followed by rapid cooling. Although cooling followed both warmings, the temperature did not closely approach the seasonal low of nearly −80° C. which was recorded on January 5. The 10-day cycle in the 20-mb. temperatures also appeared at Keflavik, Iceland (table 1), during this same period. The temperature changes at Keflavik were no less pronounced than those at the pole. Like those at the pole the Keflavik temperatures on map days were all very low, and the warmings could be missed by an inspection of just the published 10-mb. charts.

On February 1 (fig. 9), the high center at 10 mb. was

TABLE 1.—*20-mb. temperatures at Keflavik, Iceland, Jan. 25–Feb. 15, 1958*

Jan. 25	Jan. 30	Feb. 5	Feb. 10	Feb. 15
0000 GMT	1800 GMT	0000 GMT	0000 GMT	0600 GMT
−71° C.	−14° C.	−71° C.	−26° C.	−61° C.

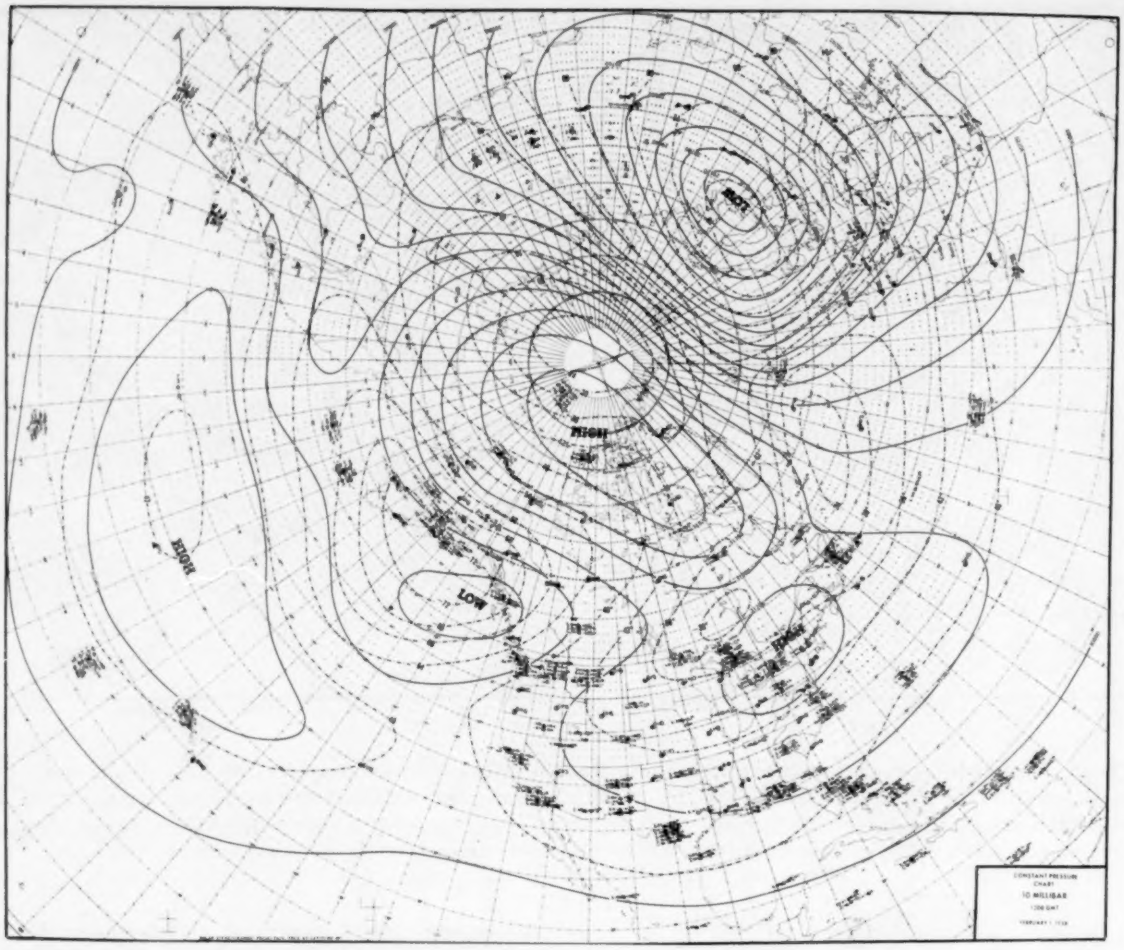

FIGURE 9.—The 10-mb. chart for 1200 GMT February 1, 1958. Contour interval 160 m.; isotherm interval 6° C. Much of the analysis beyond the area covered by the other 10-mb. charts is an estimation, based largely upon extrapolated data.

passing close to the pole. The Astrajet was stretched into a great loop that crossed over the pole and thereby split the intense polar vortex and its pool of cold air into two much weaker cold vortices, one over Europe and the other over the Gulf of Alaska. At the pole, these events climaxed a temperature increase during January of more than 50° C. and a height increase of more than 3.5 km. (Such large changes also occurred in the Keflavik area in 1957 (Teweles [13]).) The largest portion of the cold air that had surrounded the pole was carried southward over the Greenland area to Europe. There, too, large rapid changes were taking place. On January 23 when a 10-mb. temperature of —21° C. and a 10-mb. wind of 148 kt. from 250° were reported at Bitburg, the 50-mb. temperature was —50° C. at this station in contrast to —82° C. at ship "A" (62° N., 33° W.). At 50 mb., deep Lows centered northeast of Iceland and in north-central Siberia were connected by a trough across the Arctic coastline of Eurasia. Subsequent retrogression of the former Low from the vicinity of Iceland to a point over southern Greenland was accompanied by the backing of winds at Keflavik to southwesterly and by warming to —13° C. at 25 mb. at 0600 GMT on January 30. With the appearance of a deep Low over northern Europe on February 1 (fig. 9) the Greenland Low filled rapidly. At Keflavik stratospheric winds shifted to northwesterly, and the temperature at this station plunged again as indicated in table 1. The second Keflavik warming came on February 10 with the arrival of warm air from eastern Siberia where it had persisted since the beginning of the month, passing over the pole on February 7 and 8 and thence southward across Greenland.

The "explosive warming" phenomenon in 1958 as in other years was part of a hemispheric change in circulation. The preferred location for the appearance of unusually high temperatures seems to be in a portion of the Astrajet moving from a southerly direction along the eastern side of an intensifying westward-moving (retrogressing) stratospheric trough or low center. The peak temperature at a station frequently occurs as the axis of the Astrajet sweeps to the left across the station in the direction of low pressure. Near the center of highest temperature the wind decreases, and 10-mb. height increases greatly at this stage. At the same time, anomalously low temperatures appear in the northerly current west of the Low.

On the other hand when systems move eastward, the warm air center makes its way around to the northerly current ahead of the advancing ridge line. The maximum

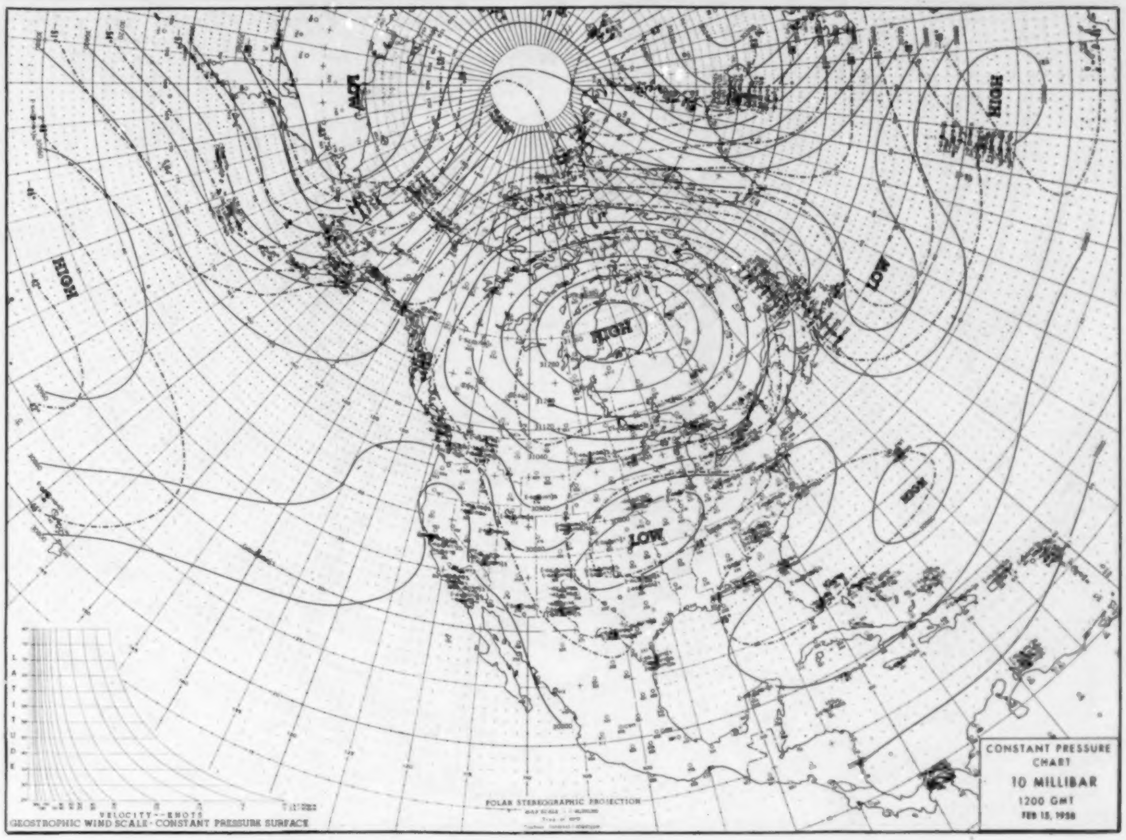

Figure 10.—The 10-mb. chart for 1200 GMT February 15, 1958, from [18]. Contours and isotherms as in figure 2.

temperatures reached seem to be less extreme than those observed with retrogressing systems. In either case, the rate of temperature change depends upon the rate at which the jet axis moves normal to itself.

8. REESTABLISHMENT OF CIRCUMPOLAR FLOW

(Mid-February to Mid-April 1958)

On February 15 (fig. 10), the temperatures and temperature gradients over the map area were about the same as those observed at the beginning of October. Only weak temperature advection was indicated. The strongest winds had decreased from 200 kt. to below 50 kt.

By late February, the weak circulation of a Low centered over Canada dominated the North American area. Hemispheric 50-mb. charts indicate that in eastern and western Eurasia there were two other low centers, both deeper and with more vigorous circulations than the one over North America.

Throughout March, weak ventilation of the polar stratosphere by mid-latitude air prevented radiative thermal equilibrium in the Arctic. By the time the cross-polar flow was halted with return of low pressure to the vicinity of the pole on April 5 (fig. 11), the sun had moved northward across the equator and temperatures rose generally over the middle and high latitudes. Although the flow in the higher latitudes of the Northern Hemisphere appeared essentially circumpolar, the 50-mb. charts show a marked eccentricity toward the Eurasian sector.

9. THE TRANSITION TO SUMMERTIME EASTERLIES

(Late April to Early June 1958)

In the second half of April 1958, the cellular structure of the contour pattern was becoming increasingly evident, and temperatures generally were rising rapidly. By May 5 (fig. 12) the circulation over North America had undergone a radical change toward meridional flow with cut off Highs and Lows. During the remainder of the month, the pressure at the pole rose rapidly and the low pressure cells in the middle latitudes faded into weak troughs. By the end of May easterly winds dominated the Arctic and the subtropics, and westerly components had almost entirely disappeared from mid-latitudes. In early June two separate bands of maximum easterlies were still apparent in the Arctic and in the subtropics, but before the arrival of the summer solstice they merged.

10. VARIATIONS IN THE TROPICAL CIRCULATION AT 10 MB.

Much of the literature on the subject of conditions at 10 mb. over the Tropics leaves the impression of an extremely steady current of easterly winds. However, some recent papers indicate the existence of substantial

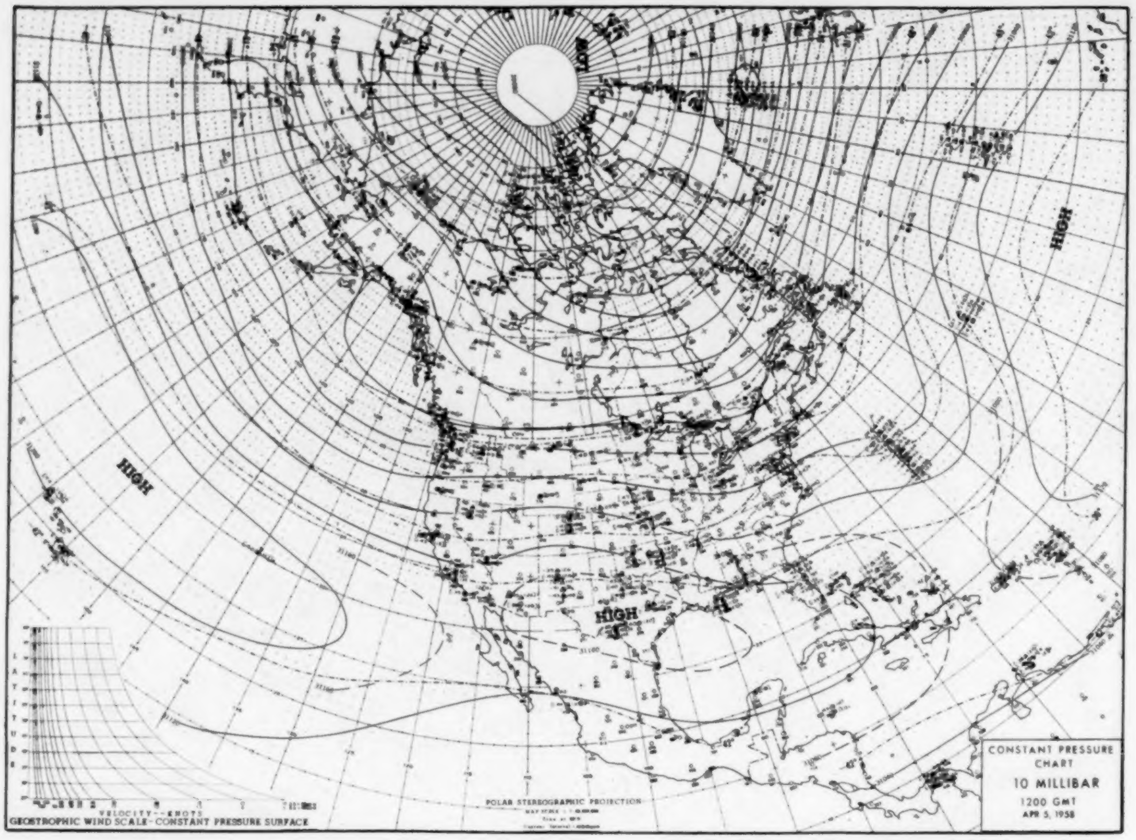

FIGURE 11.—The 10-mb. chart for 1200 GMT April 5, 1958, from [18]. Contours and isotherms as in figure 2.

year-to-year and day-to-day changes in the 10-mb. flow of the Tropics. That complete reversal of the equatorial flow may take place from one year to the next at Christmas Island (2° N., 157° W.) is shown by McCreary [5]. The majority of 10-mb. winds observed at this station in January and May of 1957 were westerly, but in the same months of 1958 they were easterly. McCreary comments on the "layered, predominantly zonal flow with great intra-seasonal steadiness and remarkable inter-annual variability." From some level above 10 mb., the layers of opposing zonal winds seem to descend slowly through the stratosphere, replacing each other with a complete cycle of about 26 months. This period is reminiscent of the famous Southern Oscillation (Berlage and DeBoer [1]) of 28 months period in the position of the sea level anticyclone of the subtropical South Pacific Ocean. Investigation of a possible relation between these periodic phenomena is recommended.

The danger of reliance upon "great intra-seasonal steadiness" is demonstrated by the rapid interdiurnal changes in the 10-mb. circulation observed over the Caribbean in late January 1960. Riehl and Higgs [7] describe a shear line that on January 28 moved northward out of South America and across the Caribbean at a speed of from 6 to 16 kt. With approach and passage of the shear line, reported easterly winds up to 100 kt. or more decreased rapidly and shifted to westerly. With the passage of a following ridge line a few days later, easterly winds again dominated the Caribbean.

Thus, 10-mb. wind forecasts based on persistence or on climatology, particularly an incomplete climatology, may occasionally be subject to great error. We conclude that even in the Tropics, operations critically dependent upon conditions at 10 mb. require the same careful forecast procedures, based on fresh, accurate data, that are used in forecasting at lower levels.

11. SUMMARY AND CONCLUSION

Although this description of the events of an entire year at an elevation of about 30 km. is necessarily incomplete, it serves to announce the availability of a recently published set of 10-mb. charts [18]. Much of the reasoning concerning cause and effect and the association of phenomena in the stratosphere is highly speculative but is included in the discussion as a basis for future speculation and investigation. It is very tempting to relate events in the stratosphere to tropospheric phenomena, such as westerly wind indices, cyclonic activity, and jet stream patterns on the one hand, or to solar disturbances and ionospheric phenomena such as sudden commencements, geomagnetic storms, and aurora on the other hand. However, the available history of stratospheric circulation is still so short that conclusions cannot be statistically validated. Even so, there are almost always enough

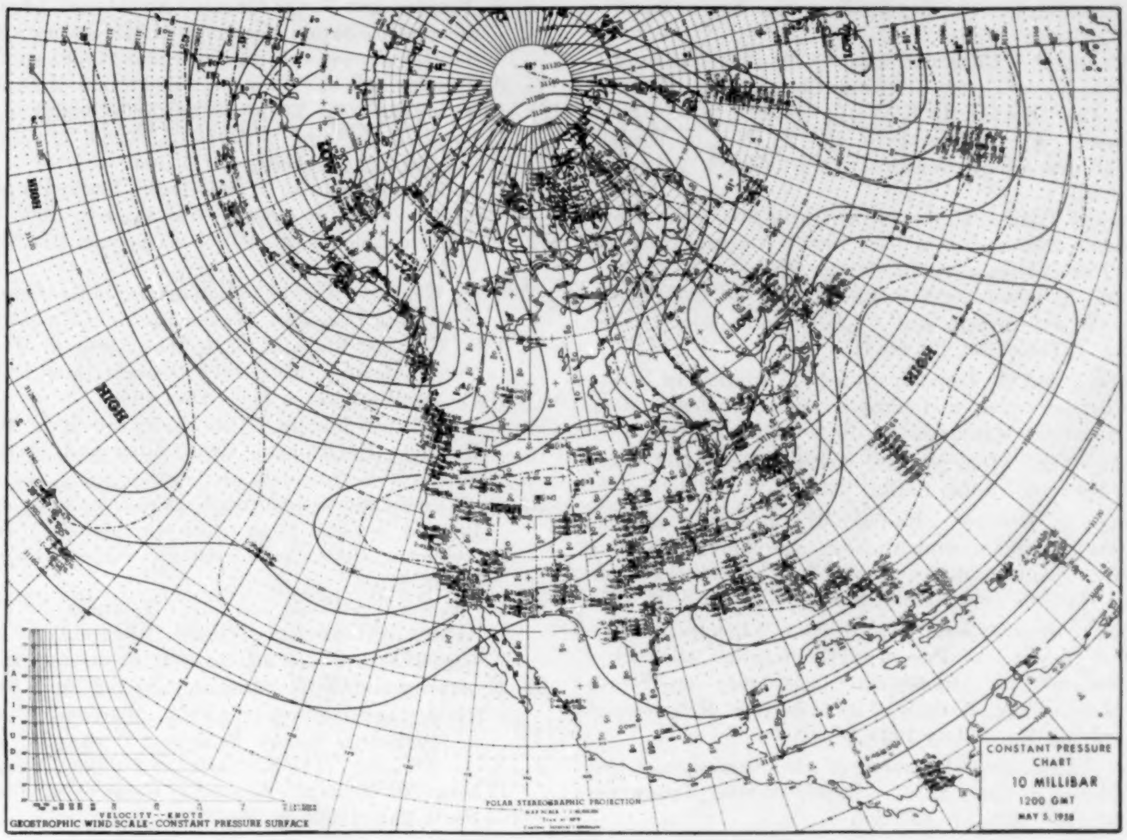

FIGURE 12.—The 10-mb. chart for 1200 GMT May 5, 1958, from [18]. Contours and isotherms as in figure 2.

analyses on record to provide a case history contradicting the theory suggested by the detailed analysis of another case history.

One stratospheric characteristic that leads to fallacious conclusions is the very slow development and movement of phenomena over a long period. Thus a very warm mass of air may appear in the stratosphere and pass over one station after the other during the course of 1 or 2 weeks. This gives ample time for any of a score of solar or terrestrial phenomena to occur and be designated as the cause or the effect of the stratospheric warming at one of the stations. A basis for many doubtful statistical conclusions is the fact that radiosonde observations rarely reach very high levels unless the radiosonde balloon is prevented from breaking by unusually high stratospheric temperatures. Thus, average values of actually observed 10-mb. data are biased toward those typical of abnormally warm situations.

Many of the problems that beset stratospheric research can be solved by more copious, more representative, and more accurate data. The balloon makers have improved the radiosonde vehicle in spectacular fashion with relatively little increase in cost. However, in many countries of the world, the radiosonde in use has scarcely any capability above the 25-mb. level. The most pressing requirement is for additional wind data through the more universal use of tracking equipment to follow the radiosonde through strong wind currents to the top of the soundings.

ACKNOWLEDGMENTS

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Provides generalized estimates of probable maximum precipitation for western United States for hydrologic design, and details what the values presented represent, how they were obtained, how they should be used, and how accurate they are.

ABNORMALLY COLD TROPOPAUSE TEMPERATURES IN THE EQUATORIAL PACIFIC

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ABSTRACT

Radiosonde observations made at Kusaie in the eastern Caroline Islands on May 15–16, 1956, reported tropopause temperatures colder than −86° C. in several instances with an extreme value of −96° C. This series of soundings is examined and compared with those made at other stations in the equatorial Pacific area.

In a recent issue of the *Monthly Weather Review*, Stepanova [1] presented a study of minimum temperatures in the lower stratosphere utilizing data taken throughout the world. The well-known meteorograph observation from Batavia, Java made in 1913 [2] was presented to illustrate the extremely cold tropopause temperatures which occasionally occur in the equatorial regions. Stepanova noted that tropopause temperatures lower than the Batavia minimum −90.9° C. have been reported in equatorial regions in recent years but presented no details of these extreme soundings.

The purpose of this note is to present data for an occurrence of abnormally cold tropopause temperatures observed in the central Pacific during May 1956. The data to be discussed were taken by stations in the aerological network established in support of Operation Redwing [1] (fig. 1) and appear in the summaries for the individual stations prepared by Joint Task Force Seven [3]. The upper-air temperature data presented in these summaries are given to the nearest whole degree Celsius. However, in the two cases to be discussed in detail, copies of the original adiabatic charts (WBAN Forms 31A–B) were obtained from the National Weather Records Center.

During the Northern Hemisphere spring months, the tropopause in the Marshall and Caroline Island areas is usually found between 90 mb. and 100 mb. at temperatures near −80° C. In these areas departures of tropopause temperatures in excess of 5° C. from this value are fairly rare. However, during two periods in May 1956 the tropopause temperatures at stations in the network shown in figure 1 were considerably colder than −80° C. The first occurence was during the first few days of the month when Tarawa, Majuro, Kusaie, Ponape, and Kapingamarangi all reported minimum tropopause temperatures as low as −86° C. with an extreme value of −89° C. at

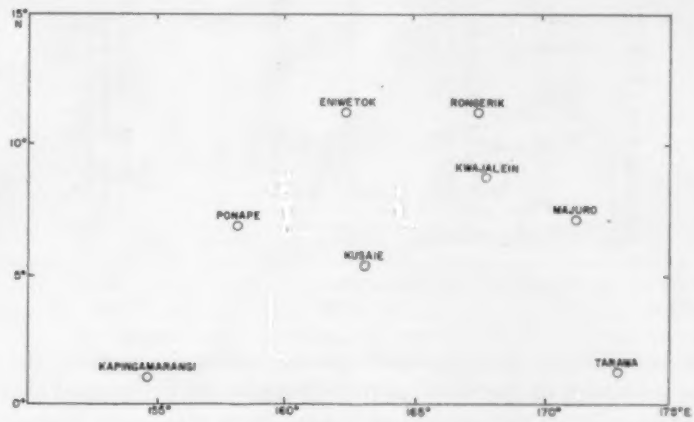

Figure 1.—Locater map for upper air stations in the *Operation Redwing* observational program, March–July, 1956.

Tarawa. A second period of low temperatures occurred near the middle of the month, but in this case the abnormally cold values were found primarily at Kusaie. A single report of −90° C. from Tarawa at 17–09 [2] does not appear realistic in view of earlier and later observations. Temperatures as low as −86° and −87° C. were, however, reported at Rongerik and Majuro. At Kusaie, temperatures colder than −85° C. were recorded between 100 mb. and 85 mb. on 12 soundings made during the period from 15–03 to 17–09 (fig. 2). In several other cases during this period, the soundings terminated before reaching temperatures of −85° C. or the tropopause. The coldest temperatures of −96.0° and −92.8° C. were reported by instruments released at approximately 15–18 and 16–08 (table 1). In these cases, the tropopause was reported at heights slightly greater than 17 km. at pressures of 87 mb. and 89 mb. All soundings made between the extreme cases (15–21, 16–00, 16–03, and 16–06) (fig. 2) failed to reach the tropopause, although three of these observations

[1] Redwing is the code name for the United States 1956 atomic test series at the Pacific Proving Ground.

[2] 0900 GMT, May 17, 1956. This notation will be used hereafter for indicating date and Greenwich hours of the observations discussed.

Table 1.—*Pressure-height, temperature, and dew point data for all mandatory and significant levels for the two soundings at Kusaie (5°20′ N., 163°01′ E.) on May 15 and 16, 1956 which showed the coldest tropopause temperatures*

1830 GMT, 15 May				0800 GMT, 16 May			
Pressure (mb.)	Height (meters)	Temperature (° C.)	Dew point (° C.)	Pressure (mb.)	Height (meters)	Temperature (° C.)	Dew point (° C.)
1007	7	25.0	23.4	1009	7	27.0	23.7
1000	64	24.5	22.6	1000	82	26.2	23.1
989		23.7	22.0	944		21.6	20.0
850	1,481	18.8	15.8	850	1,494	18.4	14.4
818		17.5	14.6	822		17.4	11.7
700	3,132	10.4	9.0	743		14.5	7.7
665		8.3	7.4	700	3,143	9.9	6.3
640		4.9	3.0	681		7.9	5.4
628		5.4	3.2	516		−3.2	−4.9
590		2.0	0.4	500	5,867	−4.0	−9.7
569		3.0	2.0	495		−4.5	−13.7
537		0.0	−1.3	486		−5.5	−16.3
518		−4.8	−8.4	472		−6.3	−13.4
502		−4.6	−16.0	436		−11.7	−17.5
500	5,867	−4.5	−15.9	420		−12.7	−27.0
482		−6.4	−20.0	400	7,588	−15.7	−25.4
438		−11.6	−16.7	394		−15.2	−20.3
400	7,588	−15.5	−20.9	300	9,700	−30.5	−33.0
342		−23.5	MB	287		−32.9	−34.9
328		−25.7	−37.6	257		−39.3	−40.8
300	9,606	−31.0	−40.1	219		−49.6	
264		−38.7	−45.2	200	12,446	−55.1	
216		−51.0		166		−67.1	
200	12,429	−55.5		150	14,212	−70.8	
174		−62.7		129		−76.3	
150	14,199	−69.3		104		−88.6	
127		−76.0		100	16,510	−89.8	
100	16,510	−88.9		89	17,150	−92.8	
87	17,270	−96.0		77		−71.5	
70		−73.6		75		−71.6	
61		−65.4		59		−73.4	
50	20,472	−68.8		58		−67.7	
48		−69.6		50	20,501	−66.1	
40		−58.5		38		−63.0	
32		−60.7		28			
25	24,839	−53.5				−58.5	
23		−51.0					
18		−47.9					

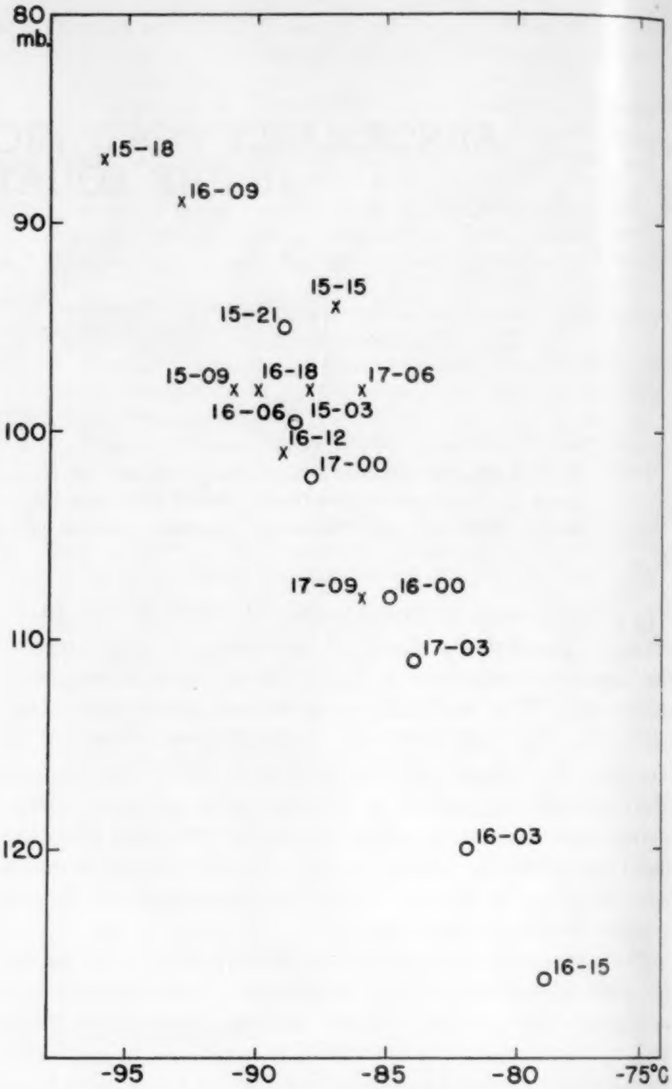

Figure 2.—A plot of minimum temperatures indicated by the soundings made at Kusaie during the period from 0300 GMT, May 15, 1956 (15–03), through 0900 GMT, May 17, 1956 (17–09). The values indicated by circles represent soundings which did not ascend above the pressure level at which the value is plotted; those represented by crosses penetrated the tropopause at the pressure level plotted on the diagram.

were made in daylight and special balloons designed for penetration of the tropical tropopause were being used [3]. The earlier of the two extreme soundings was made during the night but the later one was released at 0530 local time and would have been in sunlight at the time the lowest temperature was reported.

The portions of the two extreme soundings between the 300-mb. and the 40-mb. levels are shown in figures 3 and 4 along with soundings made at or near the same time at other stations in the network. Soundings at the same time were not available in several cases because other stations were also having difficulties in getting balloons through the abnormally cold tropopause. Temperatures at Kusaie were appreciably colder in the layer between 110 mb. and 80 mb. than those indicated at other stations. However, temperature differences were quite negligible at levels below 200 mb. and above 60 mb. (figs. 3 and 4). This agreement at the lower and higher levels offers strong evidence that the extremely cold temperatures reported at Kusaie did not arise from large systematic errors of the type occasionally found in radiosonde observations. Of course, instrumental and evaluation errors may have been present and at these very low values the temperature resolution is not very great. The smallest unit used in the evaluation procedure (0.1 recorder division) corresponds to about 0.6° C. at temperatures in the vicinity of −90° C. However, in view of the consistency of the extreme observations with those made earlier and later (fig. 2) and the fact that the upper and lower portions of the extreme soundings agree with those for the other stations (figs. 3 and 4), it is felt that errors probably did not exceed 1°–2° C.

The minimum tropopause temperatures at other stations in the network were appreciably higher during the May 15–17 period than those reported at Kusaie. At Ponape and Kwajalein, the stations closest to Kusaie, the tropopause was reported between 80 mb. and 90 mb. in several cases but temperatures were not reported colder than −84° C. Observations were being made at 6-hour intervals at Ponape and at 12-hour intervals at Kwajalein

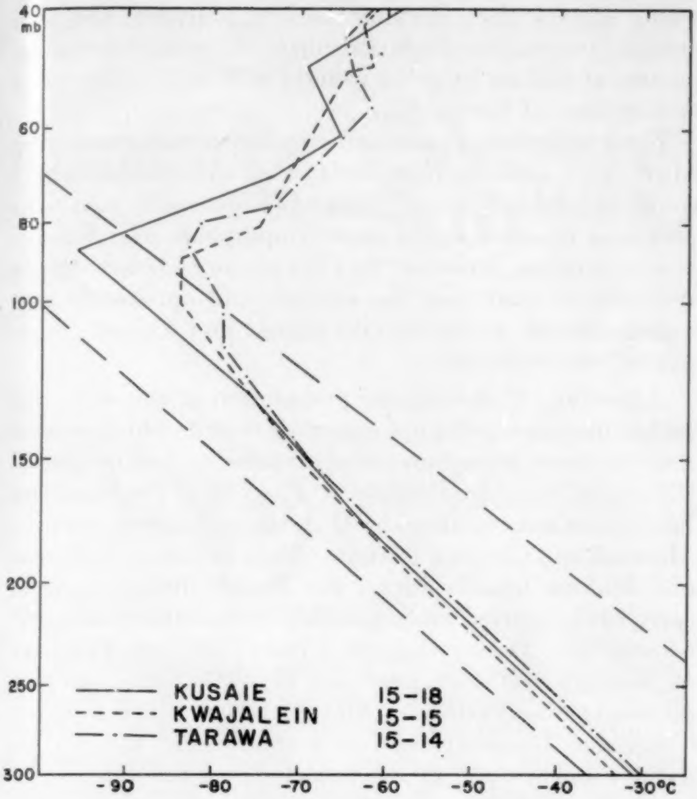

FIGURE 3.—A plot of a portion of the sounding made at Kusaie at 1830 GMT, May 15, 1956 (solid), showing an abnormally cold tropopause temperature. Soundings made near the same time at Kwajalein and Tarawa are also shown. The sloping straight lines are dry adiabats.

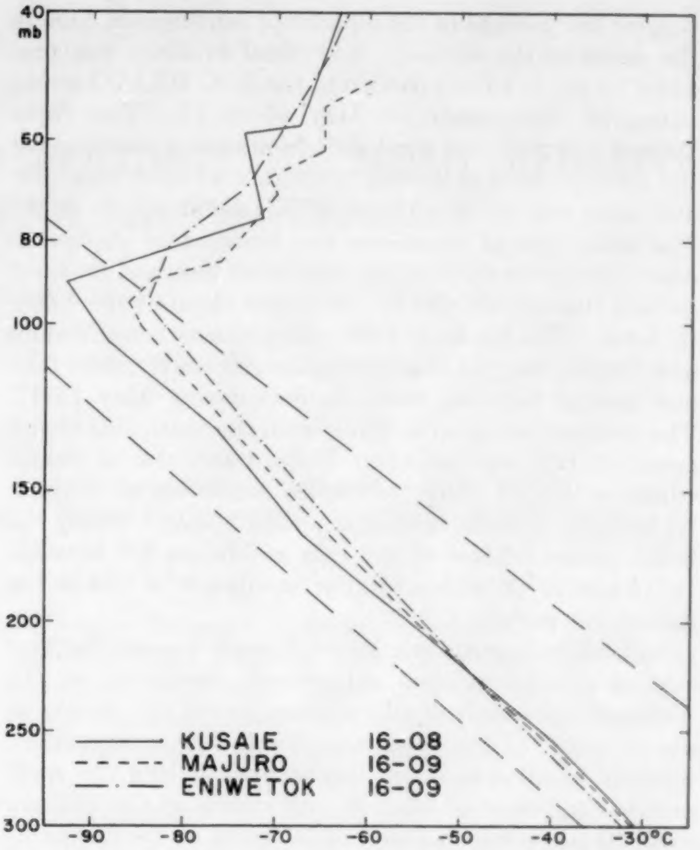

FIGURE 4.—A plot of a portion of the sounding made at Kusaie at 0800 GMT, May 16, 1956 (solid), showing an abnormally cold tropopause temperature. Soundings made near the same time at Majuro and Eniwetok are also shown. The sloping straight lines are dry adiabats.

during the period of primary interest. The coldest tropopause temperatures observed at Rongerik during the Redwing observation period (−85° C. and −86° C.) were reported at 16–15 and 17–03. Presumably some of the cold air from the vicinity of Kusaie could have passed Kwajalein undetected between 15–15 and 16–15 since the only sounding made during this period failed to reach the tropopause. Although the observations mentioned above fail to show strong evidence for an extensive area of abnormally cold air at the tropopause level, it is felt that the consistency of the observations from Kusaie is such that it would be difficult to discount the very cold temperatures reported at 15–18 and 16–08. The lowest temperatures coincided with the greatest reported tropopause heights (fig. 2) which might suggest that the cold temperatures resulted from unusual convective activity.

The weather appears to have been disturbed at Kusaie during the period of coldest tropopause temperatures. A stratocumulus overcast at heights of 1,000–2,000 ft. was reported on all except one of the 3-hourly observations between 15–03 and 16–18. Rain was reported in present weather only at 16–06 but past rain and rain within sight was reported on all observations between 15–15 and 16–06. The total rainfall during the 15th and 16th was over 2 inches but rainfalls of this magnitude are fairly common at Kusaie. The island is mountainous with a maximum elevation of about 2,000 ft. and has an annual rainfall of 200–300 inches.

Most of the rainfall at Kusaie during the 15th and 16th occurred during the two 6-hour periods immediately preceding the coldest soundings. A total of 1.09 inches fell in the period from 15–12 to 15–18 and 0.77 inches in the period from 16–00 to 16–06. During the periods of heaviest rain, the low-level winds at Kusaie were from the east and light. Speeds shown on the 3-hourly observations did not exceed 5 knots at the surface and were less than 20 knots in the lowest 10,000 ft. of the atmosphere. Beginning at about 16–03, the wind speeds began to increase and the winds shifted to the southeast. Speeds in the 3,000–7,000-ft. level attained values in excess of 25 knots on three successive observations with a maximum reported speed of 36 knots. The rain had ended by 16–09, near the time of strongest low-level wind speeds, and no additional rain was reported on the 16th or 17th.

The protracted period of rain and low ceilings and the shift of the wind from east to southeast at Kusaie clearly

suggest the passage of the equatorial convergence zone to the north of the station. Additional evidence was provided by the low-level portion of the ROC BRAVO reconnaissance flight made on May 15–16 [3]. This flight showed a pronounced wind shift from east to southeast at the 1,500-ft. level in passing through a weather area 100–200 miles east and southeast of Kusaie at about 16–00. The same type of cloudiness was reported as at Kusaie, especially to the north of the wind shift line, and for short periods the aircraft was in continuous cloud at the 1,500-ft. level. The low-level wind observations from Majuro and Tarawa suggest that the equatorial convergence zone was located between these stations during May 15–17. The weather was good at Tarawa on the south side of this zone but rain was heavy at Majuro and also at Jaluit, which is located about 125 miles southwest of Majuro. At both these atolls rainfall exceeded 5 inches during the 3-day period. Most of the rain at Majuro fell between 16–18 and 17–00 with a total accumulation of 4.04 inches during this period.

At middle tropospheric levels, Kusaie was on the west side of a well-developed anticyclonic circulation on the 15th and the center of this system passed the station at about 16–08. The upper tropospheric flow was generally westerly at all stations in the network during the early part of the period of interest with speeds at the 200-mb. and 150-mb. levels in excess of 50 knots at the northernmost stations. Speeds decreased during the 15th but at the 100-mb. and 150-mb. levels the winds retained a westerly component throughout the 16th at all stations, except for short periods at Kapingamarangi, Kusaie, and Kwajalein. It appears likely that the disturbed flow at the 40,000 to 55,000-ft. levels at Kusaie and Kwajalein during the 16th was associated with the area of cold air detected over Kusaie. From a preliminary examination of the upper tropospheric wind data at several stations, it would appear that, despite the low latitudes, the geostrophic thermal wind relationship could be used in tracing an area of cold air from the vicinity of Kusaie to the north or northeast of Kwajalein.

The weather conditions and circulation patterns during May 15–17 actually offer little or no information which could be used in substantiating the abnormally cold temperatures reported in the upper troposphere over Kusaie. It is interesting, however, that the equatorial convergence zone was located near the station, and apparently was well-developed, at the time the coldest and highest tropopauses were reported.

Addendum: Following the preparation of this note, the author has examined some upper-air records which suggest that the mean tropopause temperatures in the dry zone of the central equatorial region to the south of the Hawaiian Islands are somewhat colder than those observed over the Marshall and Caroline Islands. Data taken at Christmas and Malden Islands during the British nuclear tests in early 1957 reported mean monthly temperatures of −85° to −88° C. During the period from 1400 GMT, February 19, through 0200 GMT, February 22, 1957, there were five successive observations at Malden Island which reported tropopause temperatures colder than −92° C. An extreme value of −99° C. was reported on a daytime sounding made during this period.

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A STATISTICAL METHOD FOR ESTIMATING THE MEAN RELATIVE HUMIDITY FROM THE MEAN AIR TEMPERATURE

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ABSTRACT

This paper outlines a method of estimating the mean relative humidity from the mean temperature. Ordinary linear regression techniques are used, with a correction added to account for the systematic geographical distribution of the regression errors.

1. INTRODUCTION

The Institute of Atmospheric Physics of The University of Arizona, with the cooperation of the U.S. Weather Bureau, has recently published a comprehensive climatic summary for the State of Arizona [1]. This summary contains, among other information, estimated values of the mean monthly relative humidity at 0600 and 1800 MST for 113 cooperative weather stations in the State. It is the purpose of this paper to describe the method of estimation, which involves only the most elementary physical reasoning and statistical techniques. The simplicity of the method makes it equally applicable to arid and humid regions. However, no true reliability test can be presented, since all available data were used in determining the final relationships.

2. THE METHOD OF ESTIMATION

By making use of a simplified form of the Magnus equation presented by Holmboe, Forsythe, and Gustin [2], the author [3] has shown that an approximately linear relationship should exist between the common logarithm of the relative humidity and the air temperature. That is,

$$\log \hat{R}=c-dt, \tag{1}$$

where $\hat{R}$ is the relative humidity in percent estimated from the air temperature, t, in degrees Fahrenheit. The constants c and d are functions of the ratio of the dew point temperature to the air temperature, both in degrees absolute. Although this ratio varies only slightly, averaging about 0.95 in Arizona, even a change of 0.04 may double or halve the constant d. For this reason, and because of the absence of extensive dew point data, especially for cooperative weather stations, it was believed expedient to use least squares methods to determine the constants in equation (1). This approach has the advantages of (a) minimizing the sum of squares of the differences between observed and estimated relative humidities, and (b) yielding a measure of the goodness of fit, i.e., the correlation coefficient. It also does not directly involve any of the assumptions made in setting up equation (1).

In this study, common logarithms of the average monthly 0600 and 1800 MST relative humidities at all Arizona stations for which they are available were correlated, respectively, with the average monthly minimum and maximum temperatures. The failure of the times of these extremes to coincide exactly with 0600 and 1800 MST has no great bearing on the problem, although the resulting regression coefficients may be quite different from those expected from purely mathematical reasoning. These coefficients and the correlation coefficients for each month are listed in table 1. The sample size used varied between 21 and 22; i.e., there were at least 21 stations in the State in each month for

TABLE 1.—*The regression coefficients c and d in the expression $\log \hat{R}=c-dt$, relating the estimated average relative humidity, $\hat{R}$, in percent, to the average temperature, t, in degrees Fahrenheit. At 0600 MST, the temperature is the average minimum; at 1800 MST, it is the average maximum. Also given is the correlation coefficient, r, between the common logarithm of the relative humidity and the temperature. All coefficients were determined from data for 23 Arizona stations*

Month	Hour: 0600 MST			Hour: 1800 MST		
	c	d	r	c	d	r
January	1.936	0.00415	−0.71	2.142	0.00894	−0.87
February	1.956	0.00425	−0.78	2.174	0.00953	−0.87
March	1.960	0.00519	−0.80	2.232	0.01135	−0.82
April	1.974	0.00582	−0.77	2.219	0.01122	−0.82
May	1.988	0.00659	−0.74	2.168	0.01076	−0.74
June	1.935	0.00533	−0.61	2.032	0.00826	−0.55
July	2.097	0.00500	−0.83	2.596	0.01142	−0.84
August	2.090	0.00394	−0.80	2.434	0.00931	−0.82
September	1.995	0.00350	−0.70	2.157	0.00723	−0.70
October	1.988	0.00458	−0.78	1.986	0.00562	−0.64
November	1.943	0.00488	−0.75	2.016	0.00643	−0.72
December	1.941	0.00402	−0.73	2.049	0.00664	−0.75

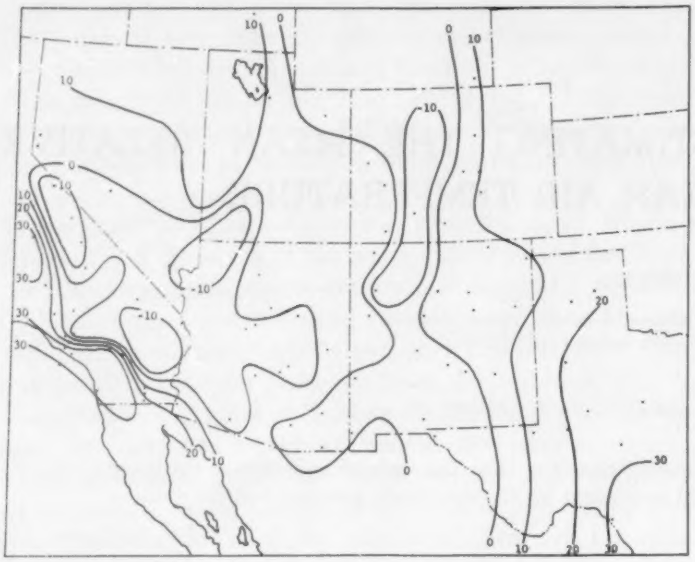

FIGURE 1.—Deviations of the observed average 0600 MST relative humidities for the southwestern United States in April from the values estimated by equation (1). The regression constants were determined from data for 22 Arizona climatological stations.

which both mean relative humidity and mean temperature data were available. With these sample sizes all correlations in the table differ significantly from zero at the 1 percent level of confidence.

In general, the best results, i.e., the highest correlations, were obtained for the winter and summer months of high humidity and the poorest results for the spring and fall months of low humidity. The standard error of estimate, not shown in the table, averages about 6 percentage units of relative humidity, ranging from about 4 to 8 percentage units. It has no systematic variations, since the months with the best correlations between temperature and relative humidity are also the months of greatest variance of these variables.

In using equation (1) to estimate the mean monthly relative humidity at stations for which only temperature data are available, it is convenient to plot it on semi-log paper, with relative humidity on the logarithmic scale. When this is done for each set of constants in table 1 a series of 24 straight lines results, one for each of the 2 hours in each of the 12 months. It is then merely necessary to enter these graphs with the average maximum or minimum

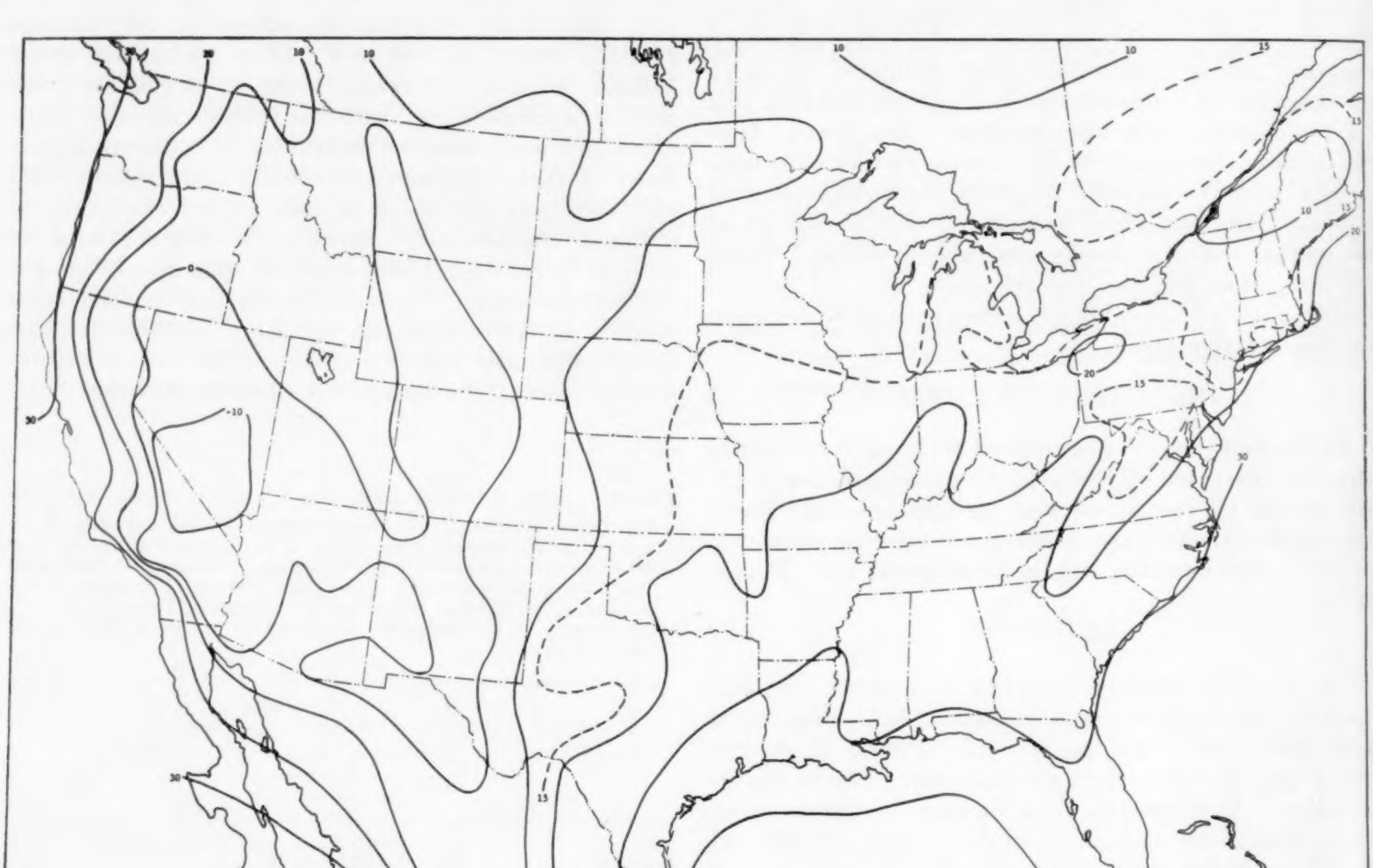

FIGURE 2.—Deviations of the average annual relative humidities (the means of the highest and lowest reported hourly values) for the contiguous United States, southern Canada, and northern Mexico from the values estimated by equation (2), using the average annual temperatures as the predictors. The regression constants were determined from data for 21 Arizona climatological stations.

temperature and read off the estimated average 0600 or 1800 MST relative humidity for a particular month.

While these estimates are probably fairly accurate, they may be improved upon by noting that the errors of estimation at the stations from whose data the regression constants were evaluated have a definite geographical pattern. This pattern may be analyzed to give errors of estimate for any station in the area for either hour and for any month. As an example, figure 1 shows the deviations of the observed relative humidities for April at 0600 MST from the values estimated using equation (1). In practice only the State of Arizona was considered. However, here the error analysis has been extended to all of the Southwest, using average relative humidities obtained by the author [3] in order to bring out more clearly the geographical distribution of errors. When these deviations from regression, denoted by e, are taken into account, equation (1) becomes

$$\hat{R}=\exp\left[2.3(c-dt)\right]+e$$

which is the expression used to estimate the monthly 0600 and 1800 MST relative humidity at 91 cooperative weather observing stations in Arizona. The first term on the right was evaluated from the graphical representation of equation (1) using the constants of table 1; the second term was determined for each station, hour, and month from analyzed state maps of the deviations from regression, i.e., deviations from equation (1).

Figure 1 has a definite climatological interpretation insofar as it delineates regions of moisture deficit and surplus in the Southwest. Thus, a station on the southern California coast recording the same average 0600 temperature in April as a town in central Arizona might be expected to have an average relative humidity more than 20 percentage units higher than the Arizona town. The same would be true for a city in southern Texas, another region of moisture surplus (relative to central Arizona). On the other hand, the Mohave Desert, southern Nevada, and the central Rocky Mountains have a moisture deficit.

For the year as a whole, the regression equation relating the logarithm of the average annual relative humidity (the mean of the 0600 and 1800 MST values) to the average annual temperature has the following form:

$$\log \hat{\bar{R}}=2.042-0.00621\bar{t} \qquad (2)$$

The correlation coefficient between the two quantities is 0.90; the standard error of estimate of the relative humidity is about ± 3.4 percent. This equation, derived from Arizona data, was applied to all first-order Weather Bureau stations in the contiguous United States, Alaska, Canada, and Mexico, using the average of the highest and lowest reported hourly mean annual relative humidities for $\bar{R}$.

The distribution of the errors of regression for the contiguous United States, southern Canada, and northern Mexico is shown in figure 2. Largest positive values, exceeding 40 percentage units, are found in the Caribbean Sea and the Atlantic and Pacific Oceans. Negative errors of regression are common only in the southern Great Basin, the Rocky Mountain system, and the Chihuahuan Desert of Mexico. In the eastern United States, where the pattern appears to be disturbed only by the Great Lakes, the Mississippi River, and the Appalachian Mountains, values range from about 12 percentage units along the northern border to over 35 units in southern Florida.

From figure 2 and equation (2) it is possible to estimate the mean annual relative humidity at any point in the country given its mean annual temperature. This estimate should be better than that derived from a map of mean annual humidity, because the latter varies greatly both horizontally and vertically, while the regression deviations are relatively insensitive to changes in topography, these changes being taken into account mainly by variations in the mean annual temperature.

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THE WEATHER AND CIRCULATION OF APRIL 1960

A Sharp Mid-Month Drop in the Zonal Westerlies Accompanied by a Temperature Reversal in the Contiguous United States

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1. HIGHLIGHTS

After reaching its highest value since early January' the speed of the westerly winds at middle latitudes sharply dropped near mid-April 1960. This drop was associated with a return of widespread blocking to higher latitudes in the last half of April, after having been absent since the middle of March, and was accompanied by a large-scale change in the pattern of planetary waves over the United States. A marked reversal in temperature regimes over the contiguous United States was also a concomitant feature of this alteration of the general circulation.

In the West above normal temperatures, including some record-breaking maxima early in the month, gave way to below normal values in the latter part of the month as a deep planetary trough became established aloft. During this period widespread frost damage to fruit was reported in many parts of the Far West and Northwest.

In the East near to below normal temperatures were replaced by record-breaking high temperatures in the latter part of the month, consonant with the planetary ridge which became established here for the first time since the latter part of December. This reversal is reminiscent of April 1957 [1] when vigorous warming in the eastern United States in the last half of the month established many new records for warmth, despite coldness early in the month.

This April was a comparatively dry one, particularly in contrast to the extremely wet April of 1957, despite similar evolution of the temperature pattern in the two months. A number of areas this month experienced the driest conditions in 30 years or more; e.g., parts of Ohio, Mississippi, Arkansas, New Mexico, Arizona, and Wyoming. Nevertheless there were some areas of excessive precipitation, principally central Montana, the Upper Mississippi Valley, some areas along the west coast, and the Southeast. Excessive precipitation in the Southeast during the first few days of the month caused flooding in this area. Considerable flooding also occurred in the Middle West and the Northeastern States due to a combination of moderate to heavy precipitation plus rapid melting of excessive snow and ice which had accumulated in record amounts in some places during the winter season.

Another highlight was the sudden development of a deep storm over Nevada late in the month, associated with retrogression of a planetary wave trough across western United States. This storm produced the lowest sea level pressure on record at Ely, Nev., 983 mb. on April 22, and ushered the coldest temperatures of the month into the Far West. The wind field aloft associated with this storm caused moist Pacific air to overrun a wedge of cold Polar Canadian air in Montana and produced a severe snowstorm with strong winds in central Montana from the 22d to the 24th. Great Falls received 16.2 inches during this time, the month's total.

Severe weather activity also developed near mid-month when a major trough was located near the Continental Divide. For example, Amarillo, Tex., reported that a tornado at Sunnyside, in Castro County, killed 3 and injured 66 on the 12th; while on the 16th, Tulsa, Okla., reported extensive tornado damage, St. Joseph, Mo., had wind gusts to 75 m.p.h., and Waterloo, Iowa, experienced damaging winds in connection with a severe thunderstorm. On the 26th, hail of baseball size fell on San Angelo, Tex., and on the 28th a tornado hit the southwestern part of Oklahoma City. Precipitation in connection with the storm system on the 27th and 28th totaled 2.16 inches, or two-thirds of the month's total at Oklahoma City.

In the Pacific Northwest a particularly stormy period caused property damage and power failures at Seattle, Wash., on the 13th and 14th, while Tatoosh Island experienced hurricane-force winds from this storm. It may be of interest that in the most recent analogous April (i.e., 1957) a similar coastal storm brought 70 m.p.h. gusts of wind at almost precisely the same time during the month.

All of the month's total rainfall at Los Angeles, Calif., 2.00 in. (about twice the normal amount), fell on the 26th and 27th, including a record 24-hour amount of 1.88 in.

2. MEAN CIRCULATION

MONTHLY PATTERN

The average circulation at 700 mb. for April 1960 (fig.

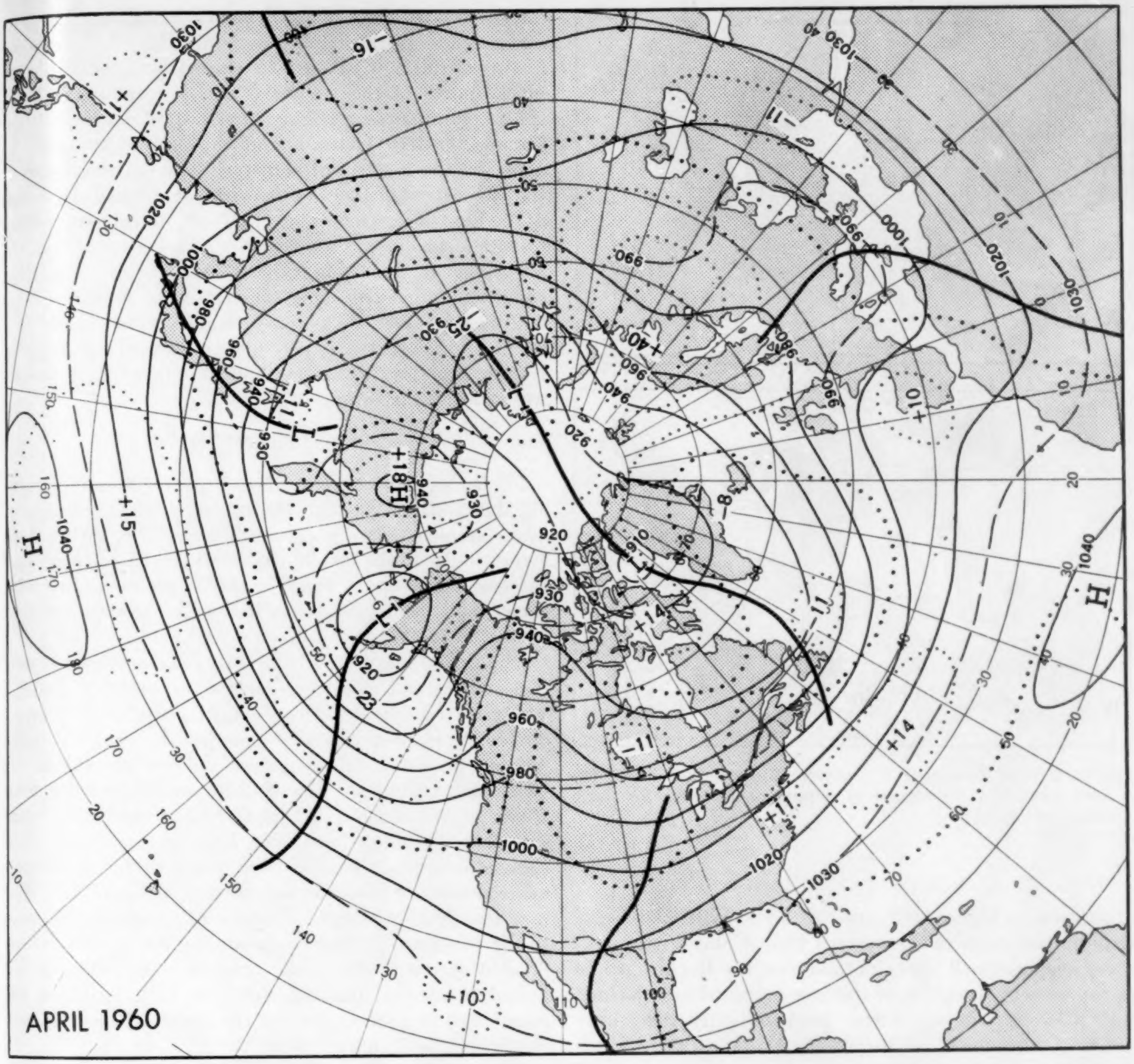

FIGURE 1.—Mean 700-mb. contours (solid) and height departures from normal (dotted), both in tens of feet, for April 1960. The trough in the central United States produced heavy precipitation in the Midwest, contributing to severe floods in the area.

1) consisted of a pattern not greatly different from normal, especially over North America, with a ridge in the West and a slightly deeper than normal trough from Iowa southwestward to Mexico. An additional center of action near southwestern Alaska and a trough extending southwestward were associated with persistent blocking in northeastern Siberia, the Alaskan Low constituting one cell of a typical "omega" block, while its twin center was displaced from its normal position to the Sea of Okhotsk. The strongest blocking in the monthly average, however, was over Scandinavia where heights averaged 400 ft. above normal.

MID-MONTH CHANGE IN CIRCULATION

For an understanding of the observed temperature and precipitation anomalies during the month (fig. 2), the two 15-day components of the April circulation are more revealing than the monthly average as a whole. The average circulation for the first 15 days of April (fig. 3A) bore a marked similarity to that of the last half of March [2]. Both periods were characterized by stronger than normal mid-latitude westerlies over the western sector of the Northern Hemisphere, averaging 11.5 m.p.s. for the first half of April. This is shown by the above normal height departures in lower latitudes and below normal

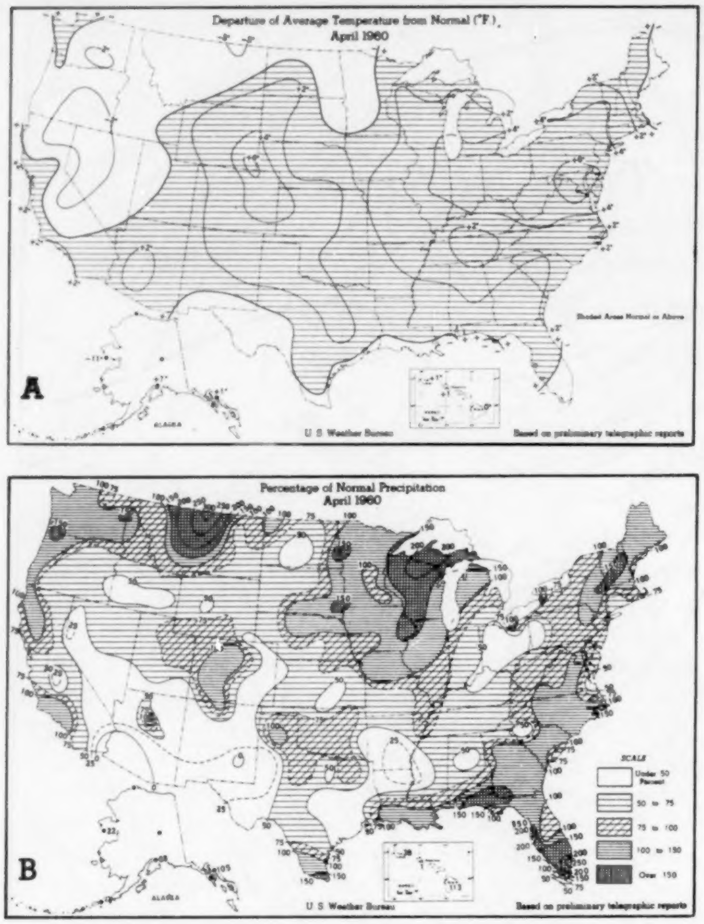

Figure 2.—(A) Temperature departure from normal (° F.) for April 1960. (B) Percentage of normal precipitation for April 1960. (From [3].)

departures at higher latitudes (fig. 3A). With a stronger than normal ridge in the western United States, temperatures averaged well above normal over the Rockies, while in the eastern trough temperatures averaged near normal (fig. 3B). Precipitation was predominantly light over much of the country for the 15-day average, except along the Gulf and Atlantic Coasts where stronger than normal southerly flow prevailed. Here 2.5-in. amounts were general along the middle and northern seaboard, with heavier amounts ranging to over 6.00 in. in the Southeast.

The marked change in the mean flow pattern which took place about the middle of April is perhaps best portrayed by the height changes between the first and last halves of the month (fig. 4). These changes took the form of hemispheric height rises at high latitudes with an array of fall centers at lower latitudes. This change pattern was a manifestation of a sudden and dramatic resurgence of blocking at high latitudes with a concomitant slowing down of the mid-latitude westerlies to an average of 7.5 m.p.s. for the last half of the month, as shown in the index graph (lower part of fig. 7).

This upheaval resulted in the average 700-mb. pattern for the last 15 days of April shown in figure 3C and its associated temperature pattern, figure 3D. An interesting feature of this flow pattern was the array of "omega"-type blocks north of the westerlies almost around the hemisphere, with blocking Highs centered over Siberia, western Canada, eastern Canada, and the North Atlantic. In addition, the reversal of planetary flow patterns between the two halves of the month, with ridge replacing trough in the East and vice versa in the West, was an outstanding feature of this month's weather. As a matter of fact, the latter part of April was the first fortnight in which ridge conditions prevailed along the east coast since the latter half of December. This may be interpreted partly as a result of the persistent tendency toward blocking in North America which is known to favor depressed westerlies to the south.

THE WEEKLY EVOLUTION

Figure 5 shows a series of 5-day mean 700-mb. patterns at approximately weekly intervals, with observed temperature anomaly classes superimposed. The period April 5–9 is similar to the first 15-day average with a trough near the east coast and a ridge in the West, associated with cooler than normal conditions in the East and warmer than normal in the West.

The period April 12–16 (fig. 5B) shows conditions near mid-month, and closely resembles the monthly pattern. An over-extension of the wavelength across North America due to rapid progression of the eastern trough into the Atlantic favored the development of a new trough near the Continental Divide. The resulting backing of the mean winds over the central United States resulted in considerable warming from the Rockies eastward, while cooling occurred in the Far West, as shown by the temperature departure from normal pattern in figure 5B. The new trough also brought a return of heavy precipitation to the Midwest, further compounding the severity of the flood situation in this area. Immediately following this period, a strong blocking surge at high latitudes was manifested in a sharp drop in the speed of the temperate westerlies (fig. 7, lower chart).

Figure 5C depicts the mean flow and temperature anomaly classes for the period April 21–25. This 5-day period closely resembled the 15-day average for the latter half of the month and had the weakest westerlies at mid-latitudes since February, 5.8 m.p.s., or 2.3 m.p.s. below normal. Ridge development off the Pacific Coast together with westward migration of the Canadian block to the Great Slave Lake area provided circumstances favorable for a much deeper than normal trough in the Far West and resulted in retrogression of the trough which had been near the Continental Divide at mid-month. The consequent strengthening of the northerly flow, relative to normal, along the West Coast and of the southerly flow over the central United States resulted in the greatest contrast in temperature of the month with record heat in the East and cold in the West (fig. 5C).

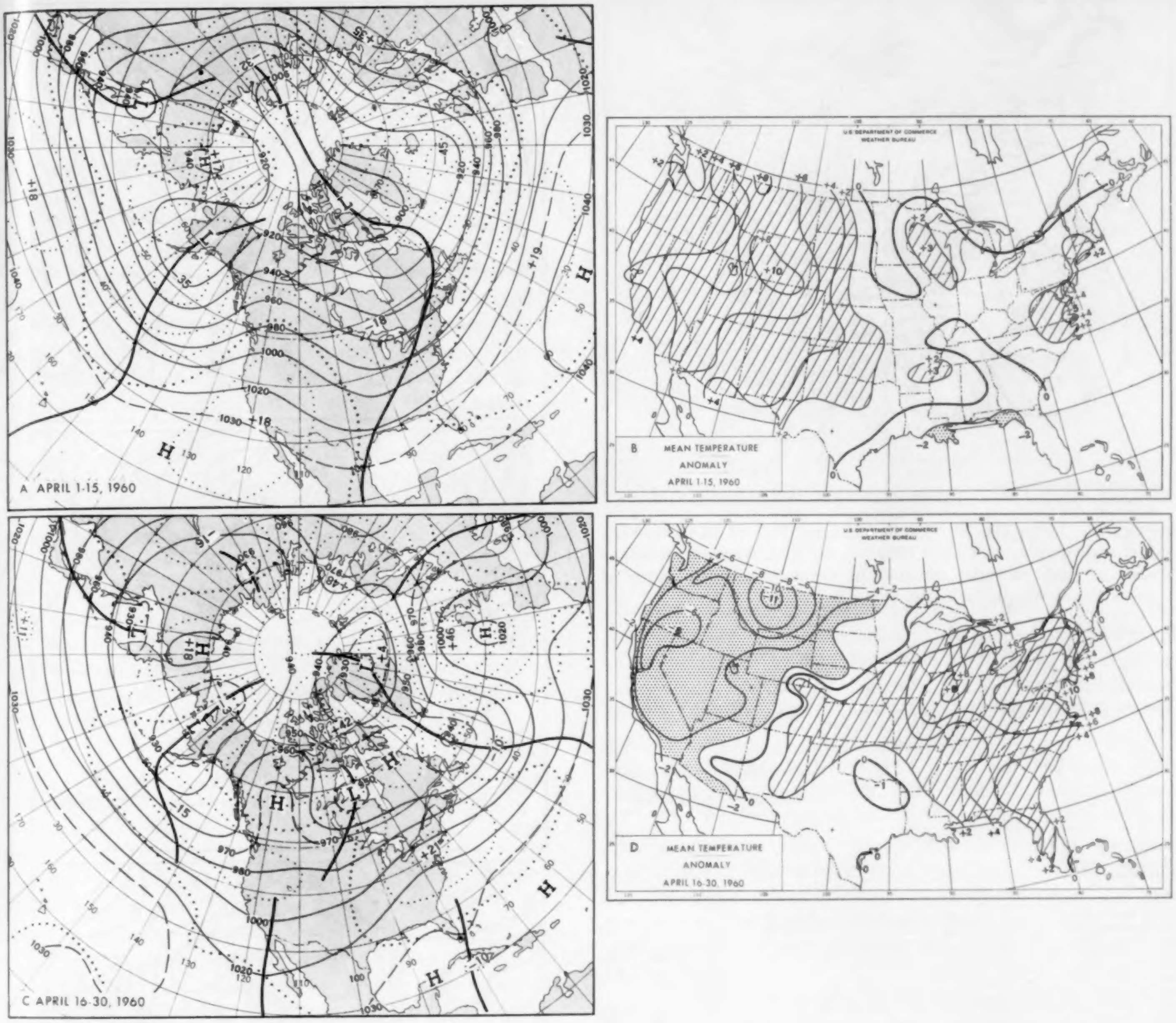

Figure 3.—(A) Mean 700-mb. contours (solid) and height departures from normal (dotted), both in tens of feet, for April 1–15, 1960. (B) Temperature departure from normal (° F.) for April 1–15, 1960. (C) Mean 700-mb. contours (solid) and height departures from normal (dotted), both in tens of feet, for April 16–30, 1960. (D) Temperature departure from normal (° F.) for April 16–30, 1960. The reversal of the circulation and temperature patterns over the contiguous United States was noteworthy.

3. TEMPERATURE CHANGES AND EXTREMES

It is probably not surprising that the great upheaval and associated reversal of the circulation during the month over North America were associated with extreme temperature changes and record-breaking temperatures. This was related to the enormous pressure changes which occurred to bring about such an evolution and the associated surface storminess such as that which produced the record low pressures in Nevada in the latter part of the month. The development of deep surface storms (cyclogenesis) acted to exaggerate the temperature changes which normally would be associated with planetary wave redistribution, primarily through the development of extreme contrasts in low-level advection.

Thus new maximum temperature records for individual dates were set at scores of stations throughout the continental United States: in the East in the latter part of the month, and in the West early in the month. However, in Alaska high temperatures occurred near month's end when the Canadian block had retrograded to this vicinity.

In the eastern United States the heat wave was the more spectacular because of the record breaking cold which preceded it during March [2] and part of early April. So sharp were the contrasting regimes in the East between

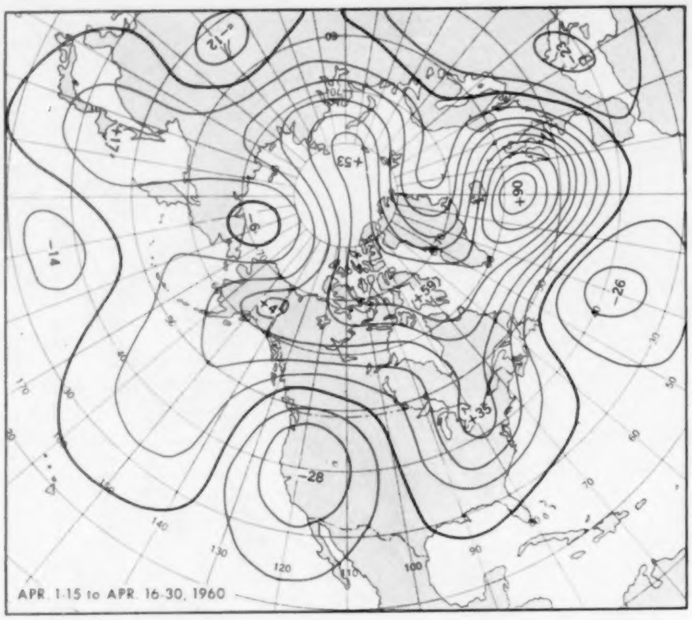

FIGURE 4.—Mean 700-mb. height changes (tens of feet) between first and last halves of April 1960 (see fig. 3). Widespread height rises at high latitudes resulted in dramatic slowing down of westerlies at middle latitudes.

TABLE 1.—*Some record temperatures for indicated dates observed during April 1960*

	New record maximum	Date	New record minimum	Date
Birmingham, Ala			31	10
Montgomery, Ala	89	25		
Fairbanks, Alaska	74	30		
Prescott, Ariz	82	5	24	25
Yuma, Ariz	101	9		
Little Rock, Ark	89	23		
Sacramento, Calif	86	4		
San Diego, Calif	92	2		
Denver, Colo	80	10	22	30
Hartford, Conn	81	22		
Wilmington, Del	89	23		
Washington, D.C	95	23		
Rome, Ga			23	11
Boise, Idaho			20	16
Evansville, Ind	85	22	25	10
Peoria, Ill			21	10
Burlington, Iowa	84	23	20	10
Sioux City, Iowa	94	22		
Louisville, Ky	91	23		
Caribou, Maine			9	11
Baltimore, Md	95	23		
Grand Rapids, Mich	83	22		
St. Cloud, Minn			14	9
St. Louis, Mo	91	23	26	10
Billings, Mont	80	5	23	25
Omaha, Nebr	92	22		
Las Vegas, Nev	94	5	41	17
Newark, N.J	91	25		
Albuquerque, N. Mex	84	7		
Binghamton, N.Y	87	23		
Raleigh, N.C	93	24		
Cincinnati, Ohio	89	23		
Philadelphia, Pa	92	25		
Pittsburgh, Pa			21	11
Columbia, S.C	93	25	29	11
Greenville, S.C	85	22	33	11
Sioux Falls, S. Dak	93	22		
Nashville, Tenn	85	22	28	10
Corpus Christi, Tex			44	4
Salt Lake City, Utah	82	9	24	17
Burlington, Vt	76	17		
Richmond, Va	96	26		
Spokane, Wash			26	22
Yakima, Wash	78	4		
Parkersburg, W. Va	89	23		
Milwaukee, Wis	84	22	20	10
Sheridan, Wyo	76	5		

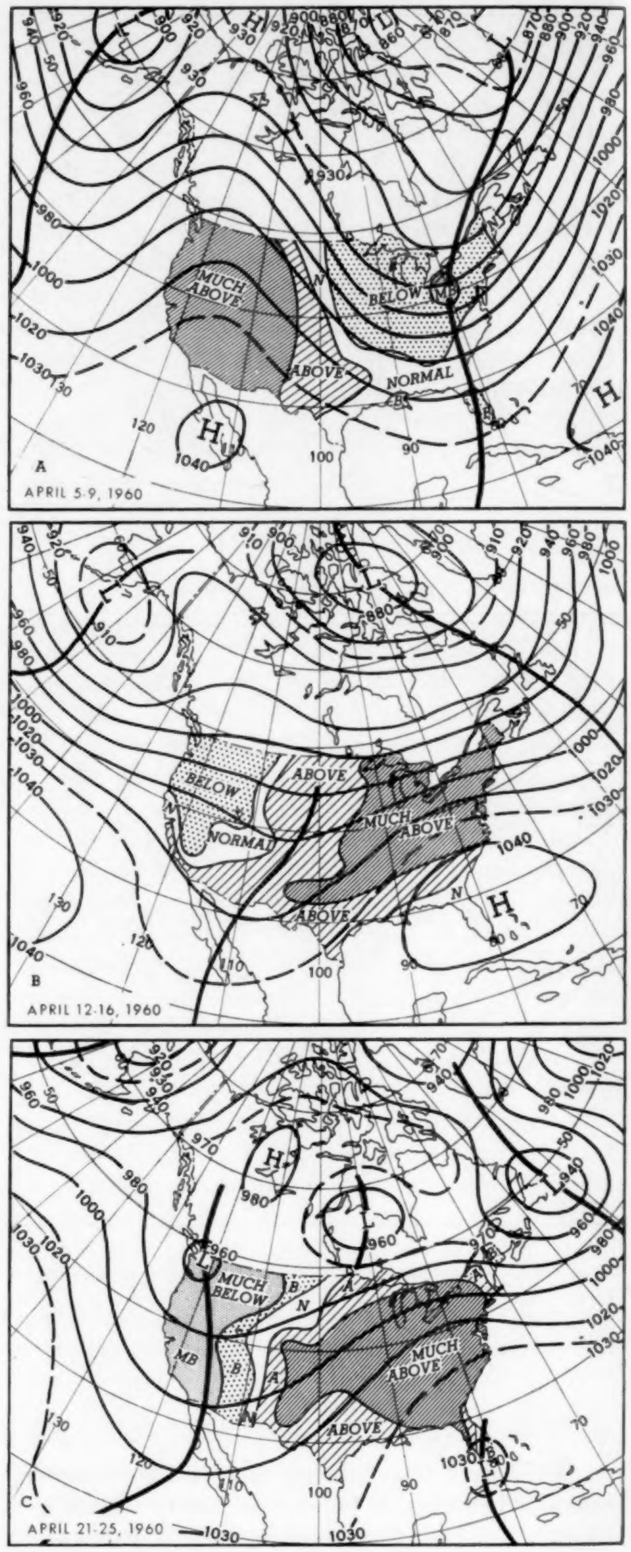

FIGURE 5.—5-day mean 700-mb. contours (solid), tens of feet, and observed temperature anomaly classes for (A) April 5–9, (B) April 12–16, and (C) April 21–25, 1960. The most noteworthy aspect of this evolution was the complete reversal in phase of the planetary wave over the contiguous United States.

the two halves of April, as well as between April and the preceding March, that winter seemed to give way abruptly to midsummer during a brief span of time near the middle of the month. Figures 3B and 3D reveal this reversal of temperature anomalies between the two parts of the month. It may also be inferred that 15-day average temperatures cooled 10° to 20° over much of the intermountain area of the West with the greatest cooling in Montana, while marked warming occurred from Illinois eastward to the Middle Atlantic coast.

In addition to numerous record maximum temperatures for individual dates, new record maxima were established for the entire month and for so early in the season. Furthermore, a number of cities near the Atlantic coast reported the highest mean temperature ever recorded for the month of April; e.g., Washington, D.C., Baltimore, Md., and Richmond and Norfolk, Va. Norfolk reported five consecutive days of record maxima, climaxed by 97° F. on the 26th. The warmest period in the East was about the 22d to the 26th (fig. 5C) when daily average temperatures rose to 26° above normal in some places. In the same period daily mean temperatures in parts of the West plunged to 20° below normal with widespread damage to fruit crops in the Pacific Northwest. Many new minimum temperature records for individual dates as well as for so late in the season were set in the West during this period. Many of the record temperatures for both extremes are given in table 1.

4. FLOODS

Most of the areas of heavy precipitation east of the Rockies this month experienced moderate to severe flooding. The severity of the flooding in some areas, such as the Mississippi and Missouri River Basins in the Midwest and the Connecticut River Basin in New England, was compounded by rapid thawing of heavy to record-breaking late season snows.

In the Midwest early in the month record-breaking floods developed along the main stem of the Mississippi River from Burlington, Iowa to Quincy, Ill., and the highest stages since 1947 were reported from Hannibal to Winfield, Mo. During early April serious flooding also occurred in portions of the Missouri Basin. The greatest flooding since the turn of the century was reported at Akron, Iowa. The Missouri River flood extended from Nebraska City, Nebr., to the mouth with a 5–6-ft. overflow from Nebraska City to Atchison, Kans., exceeded at Rulo, Nebr., only by the record flooding in April 1952. Ice jams caused considerable flooding along the Elkhorn River in northeastern Nebraska.

Near the middle of the month heavy rains from Oklahoma to Illinois (up to 8 in. locally in Missouri) resulted in new overflows along streams that had only recently returned to their banks from the early April overflows. The Mississippi again left its banks from Hannibal to Louisiana, Mo., and the entire Illinois River was also in flood again near mid-month. In addition, rapid snowmelt produced some light overflows in the Red River of the North Basin in Minnesota, and flooding also developed again in places in the Kansas River Basin in Kansas. Later in the month, heavy rains resulted in considerable flooding in the northern counties of Wisconsin and the western counties of Upper Michigan.

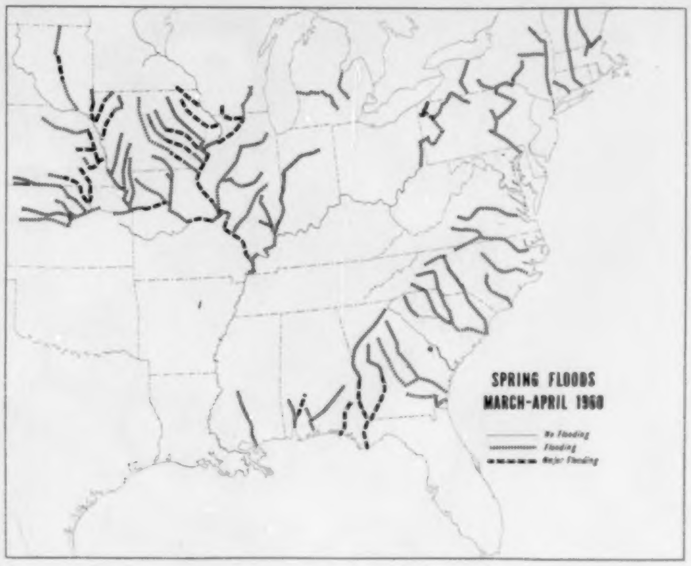

Figure 6.—Areas affected by flooding during late March and early April 1960. (Preliminary data from [3].)

In the Northeast, the most serious flooding since 1938, except for the flooding by rains from hurricane Diane in 1955, occurred along the Connecticut River in New England. The highest stages in several years were reported in the Merrimack River Basin in New Hampshire and Massachusetts. Minor to moderate flooding also occurred in the Hudson-Mohawk Basin in New York and along the entire Susquehanna River in New York and Pennsylvania.

In the Southeastern States the most significant flooding occurred in the Gulf drainage streams from the excessive rains early in the month. The most serious overflows occurred in parts of Georgia, Alabama, northwestern Florida, and Mississippi.

Areas affected by flooding during late March and early April are shown in figure 6. This résumé and figure 6 are based on the preliminary data reported in [3].

5. RESUMPTION OF BLOCKING AND THE NEW INDEX CYCLE

Above normal westerlies prevailed in the western part of the Northern Hemisphere for almost exactly one month, from the latter part of March to the latter part of April. This was the first significant period of high index since late December 1959, when the protracted index cycle of the recent winter began (lower part of fig. 7). Such a major index cycle is a frequent concomitant of the winter season [4], the most recent previous case being that of

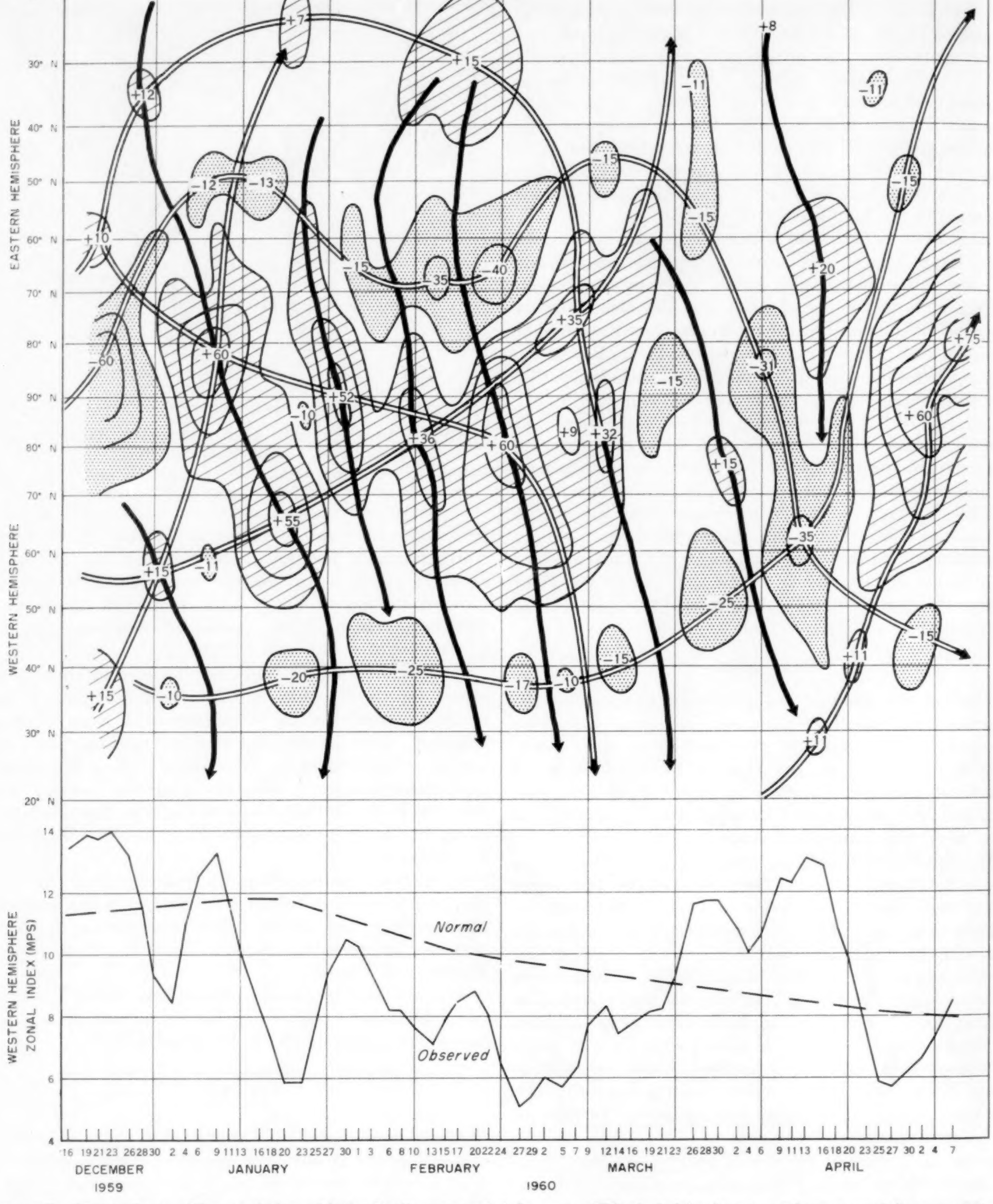

Figure 7.—Upper chart.—Time variation of latitudinally averaged 5-day mean 700-mb. height departures from normal (in tens of feet). Western and eastern halves of the Northern Hemisphere were averaged separately. Main feature was the predominance of positive height departures at high latitudes from late December to March and again in late April. See text for explanation of continuity of height anomaly cells. Lower Chart.—Time variation of 5-day mean 700-mb. zonal index in meters per second for the western section of the Northern Hemisphere between 35° and 55° N. The westerlies were above normal (dashed curve) from late March to April when negative anomalies dominated the high latitudes, and sank below normal when blocking resumed in late April.

the winter of 1958 [5]. These cycles are generally accompanied by persistent or recurrent "blocking" which in its broadest sense refers to the slowing down of the westerlies. This is brought about by relaxation of meridional pressure gradients due to above normal pressures (or positive height departures) at high latitudes and negative departures at low latitudes.

In order to shed some light on the resumption of blocking and the sudden depression of the westerlies in the latter part of April, the upper portion of figure 7 was prepared. This portrays the time variation of latitudinally-averaged 5-day mean departure from normal of 700-mb. height. Western (0°–180° W.) and eastern (0°–180° E.) departures were separately averaged for each 10° latitude circle. The horizontal scale encompasses a period of about 4½ months extending from late December 1959 to early May 1960. The vertical scale represents increasing latitude in the western section of the Northern Hemisphere to the North Pole (90°), thence decreasing latitude in the eastern section, beginning and ending at latitude 20° N. This arrangement was planned in the hope of facilitating the detection of inter-sectional or transpolar exchanges of height anomalies, as well as the behavior of these anomalies relative to a broad space-time frame of reference. Since little is known about the physical aspects of continuity on a long time scale, the sequences of anomaly cells indicated in figure 7 are not necessarily unique. However, the individual 5-day mean anomaly patterns (prepared three times a week) were also considered.

In the upper part of figure 7, apparently very-long-period oscillations of height anomaly centers have been connected by double-lined arrows. In addition there appear to exist frequent short-period surges more or less orthogonal to the long-period oscillations. These have been indicated only for positive (or diminution of the negative) anomaly activity by heavy single lines and will be referred to as "transversals." The majority of these transversals appear to slant down the chart to the right, suggesting that the surges they represent originated primarily in the eastern part of the Northern Hemisphere and terminated in the subtropics of the western part. An additional set of negative transversals could have been drawn between the positive transversals but were omitted for clarity. It may be that these shorter-period surges are related to the circumpolar pressure waves discussed by Namias [6].

The remaining discussion is concerned primarily with the very-long-period oscillations shown by the double arrows in figure 7. The most obvious feature is the prolonged predominance of above normal heights at high latitudes from the end of December to the middle of March, when the westerlies remained well below normal in speed and latitude except for a brief period in early January. From mid-March to mid-April negative height anomalies were in the ascendancy at high latitudes, at which time the westerlies were stronger than, and north of, normal. Clearly evident in figure 7 is the dramatic resumption of above normal heights in the polar regions near mid-April, associated with another sharp drop in the westerlies similar to that of late December 1959, and signaling the onset of a new index cycle.

It may be of value in this connection to study the long-period continuity of anomaly cells of like sign and their relationship to those of opposite sign. Perhaps the most obvious sequences are those of the negative cells which dominated lower latitudes almost continually during winter months. The cellular configuration may be interpreted to be a result of periodic intensification and diminution by the short-period anomaly surges of alternating sign (the transversals). The negative cells in the west increased in intensity with a northward trend from early January to mid-February but further northward movement, which might have ended the index cycle, appeared to have been thwarted by the existence of a long-period trans-sectional wave of height rises which, late in February, depressed the westerlies again to the lowest value of the year. Later in February the negative cells again began an ascending trend, and during late March and April they met with increasing support at higher latitudes from transpolar waves of negative anomaly from the east. This culminated in early April in an interaction at higher latitudes of the two long-period surges of negative anomaly from the opposite sides of the hemisphere. At this time the westerlies in the western part achieved their northernmost position and maximum speed since late December 1959. After the paths of the long-period negative cells diverged, blocking returned in strength to the higher latitudes in late April.

The sequences of the positive cells in figure 7, which constituted the blocking regime at higher latitudes, were not so easily discerned as those of the negative centers, due to their more complicated nature. It appears, however, that just as there were at least two distinct loci of negative cells, one in each part of the hemisphere, which were clearly defined because of their large separation, there probably also were two loci of positive centers. However, at higher latitudes these loci were difficult to distinguish because of their proximity. Therefore the connections of the positive cells which have been drawn at higher latitudes in figure 7 should be regarded as tentative, suggesting only one of the possible interpretations. This solution suggests a continuity of two simultaneous blocking surges at higher latitudes, the cellular character being the result of interference by the orthogonal short-period transpolar anomaly surges of alternating sign depicted by the single-line transversals.

The continuity of the averaged height anomalies in figure 7 suggests the possibility of some general lag relationships. For example the index cycle which started in late December 1959 and the one in late April were preceded by positive height departures of about 100 ft. or more in the subtropics. This condition seemed to apply equally well to both parts of the hemisphere prior to the onset of both major index cycles. In addition, it may be observed

from figure 7 that around mid-February in the eastern part of the hemisphere the subtropical height departures achieved a value of 150 ft. and, perhaps as a consequence, in March, the westerlies receded southward in that area. It thus appears that the eastern section had a double cycle during the winter, while the western part had only one prolonged major cycle, apparently due to the fact that subtropical positive anomalies averaged over the western part never achieved a sufficiently large value, such as observed in mid-December and mid-April. It should be noted that these suggestions are not inconsistent with the interpretation of "blocking action" in terms of large-scale energy considerations by Rex [7], who pointed out that narrow, high-velocity westerly streams often break down in a lower-energy mode of flow associated with amplification and low index.

From the foregoing discussion, one might speculate that index cycles commence after the sectional subtropical height anomalies have surpassed a certain positive value, perhaps near 100 ft. Although this value seems small compared with the values observed at middle and high latitudes, it must be realized that the degree to which an accumulation or deficiency of air is reflected by the anomaly value is markedly affected by latitude. Because of the convergence of the meridians, relatively small departures from normal at low latitudes possess greater potential if in some manner the increased mass is propagated to higher latitudes.

The index graphs for the 700-mb. subtropical and Polar westerlies (not shown) in the western section of the hemisphere verified the fact that the diminution of the westerlies preceding both the December and April declines at middle latitudes appeared first in the subtropics and last at the polar latitudes. This bears out the suggestion implied in figure 7 that the averaged value of the subtropical positive anomaly may be important and perhaps critical in the subsequent evolution of the index cycle.

It should be pointed out, however, that the inferences discussed above may not apply to other cases. They do suggest an area for future study. In fact even the method of presentation shown in figure 7 should be subject to further study since the particular 180° longitude sectors used for averaging were chosen primarily because they were most conveniently obtainable in this form from the punched card data. Actually a much better division of the Northern Hemisphere, from the standpoint of blocking, would be one which does not split a well-known homogeneous blocking regime such as exists near the 0° meridian.

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